VOL. 2 No. 4 APRIL 1937

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
N.V. PHILIPS' GLOEILAMPENFABRIEKEN

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, HOLLAND

NUCLEAR PHYSICS

by W. DE GROOT.

Summary. In this article a survey is given of the main principles of the physics of the atomic nucleus, a subject which is becoming increasingly important in modern technology.

Introduction

The growing importance of the physics of the atomic nucleus, or "nuclear physics", in the technical design of high-tension apparatus, discharge tubes, counters, relay valves, amplifiers, etc., calls for a brief survey of the development of this branch of knowledge during the last quarter of a century.

The "Atomic Nucleus" Conception

The concept of the atomic nucleus is due to Rutherford, who from observations made in 1912 on the dispersion in various substances of alpha-particles emitted by radium (alpha rays) deduced that at the mass centre of each individual atom there is a heavy nucleus at which the bulk of the atomic mass is concentrated.

Fig. 1. Model of atom. The circle represents the extreme boundary of the atom and the dot the nucleus. Actually the diameter of the nucleus is about 1/30000 of the diameter of the atom.

This conception of atomic structure is shown schematically in *fig. 1*, where the large circle represents the extreme boundary of the atom and the dot at the centre the nucleus. The diagram is not drawn to scale, for this would require the circle to have a diameter of e.g. 3 m and the dot a diameter of only 0.1 mm.

The space between the nucleus and the boundary of an atom is occupied by the orbits of the electrons. The atomic theory propounded by Bohr in 1913 furnished a method for investigating these electronic orbits, and the general conclusion may be drawn from Rutherford's experimental work and Bohr's theory of the validity of the periodic classification of the elements that the atomic nucleus possesses a positive charge which according to van den Broek and Moseley is equal to

$$Z \cdot e$$

where e is the socalled elementary charge (approximately $4.8 \cdot 10^{-10}$ electrostatic units) and Z is an integer, the so-called atomic number. The atomic number and the laws governing the orbits of the electrons determine the chemical properties as expressed by the periodic classification of the elements, this classification being one of the corner-stones of modern chemistry.

Physical and Chemical Atomic Weight

In addition to the charge of the atomic nucleus its mass is also of fundamental importance. Since the mass of the nucleus and that of the associated atom bear a simple relationship to each other, and the atomic mass, contrary to the nuclear mass, can be determined directly by experimental means, it has become a common practice to introduce the atomic mass (M) in discussions of the nuclear mass (M_k). The relationship between these two masses is given by the expression:

$$M = M_k + Z\, m_e \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where m_e is the mass of the electron. The chemist generally employs as the unit of atomic mass the

sixteenth part of the mass of an oxygen atom. Expressed in this unit the electron has a mass of 0.00055, and since for all atoms $Z < M$ it follows that the nuclear mass accounts for more than 99.95 per cent of the atomic mass. In 1913, J. J. Thomson discovered that the majority of the chemical elements are mixtures of isotopes, i.e. compounded of various species of atoms with different masses and the same nuclear charge, hence with identical or nearly identical chemical properties. Since that time a distinction has been drawn between the chemical and physical atomic weight (isotopic weight). The latter is expressed in terms of a unit equal to $^1/_{16}$ the mass of the oxygen isotope O^{16}. The chemical element oxygen is thus itself a mixture of isotopes, viz., O^{16}, O^{17} and O^{18} in a ratio of 99.8 : 0.03 : 0.16, such that:

$$O_{\text{chem}} = \frac{16\cdot 99.8 + 17 \cdot 0.03 + 18 \cdot 0.16}{16 \cdot 100} O^{16} = \\ = 1.00022\ O^{16}.$$

The relationship between the chemical atomic weight (M_{ch}) of an arbitrary element and the physical atomic weight of its isotopes, M_1, M_2 . . . may be represented as follows:

$$M_{\text{ch}} = \frac{1}{1.00022} (p_1 M_1 + p_2 M_2 \,.\,.) : 100, \quad (2)$$

where p_1, p_2 . . . are the percentages of the various isotopes present. The agreement between the atomic weights obtained by physical methods from equation (2) and the atomic weights determined by direct chemical methods is usually very close.

Composition of the Nucleus. Binding Energy

A characteristic of the isotopic weights discussed above is that to a very close approximation they are all whole numbers. To define the nucleus there has therefore been introduced, in addition to the integer Z, a second integer A, the mass number, which is the integer nearest to the atomic weight of the isotope. For the hydrogen nucleus $Z = 1$ and $M = 1.0081$, and hence $A = 1$. The hydrogen nucleus is the simplest nucleus known and is in fact regarded as a single elementary particle; as such it has been given the characteristic name of "proton".

In addition to the proton, physical research has during the last five years discovered still another elementary particle, the neutron (Chadwick, 1932). For the neutron $Z = 0$, $M = 1.0090$, hence again $A = 1$. Since the discovery of the neutron, the general assumption has progressively gained ground that other nuclei are built up from protons and neutrons; it is thus assumed that a nucleus with the mass number A and the atomic number Z is composed of

$$Z \text{ protons} + N \text{ neutrons},$$

where $N = A - Z$ [1]). It is evident that in this way we arrive at a nucleus with the correct charge and approximatively the correct mass. Yet on a closer examination it is found that the mass of the nucleus is a little smaller than those of its components. Take as an example the nucleus of an atom of the reference element O^{16}; for this atom $M = 16.000$ by definition, while the weight of its components is:

$$8 \cdot 1.0081 + 8 \cdot 1.009 = 16.1368 \text{ }^{2})$$

The difference is due to the liberation of binding energy on the combination of protons and neutrons to form a single nucleus; the magnitude of this energy is given by a well-known equation in the theory of relativity as equal to the difference in mass multiplied by the square of the velocity of light. As the true mass of $^1/_{16}$ of the atom O^{16} is $(1/6.06) \cdot 10^{-23}$ gram and the velocity of light is $3 \cdot 10^{10}$ cm per sec, the binding energy of the oxygen nucleus is found to be:

$$\frac{0.1368}{6.06} \cdot 10^{-23} \cdot (3 \cdot 10^{10})^2 = 0.000203 \text{ erg}.$$

Another unit used for expressing the atomic energy is the electron-volt, which is the energy acquired by an elementary charge when it passes through a potential gradient of 1 volt. These units are related to one another as follows:

$$0.001 \text{ atomic-weight unit} = 1.49 \cdot 10^{-6} \text{ erg} = \\ = 0.93 \cdot 10^6 \text{ eV} = 0.93 \text{ MeV}.$$

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[1]) The nucleus and hence the associated atom are completely determined by N and Z or also by A and Z. A nucleus could be adequately described by these two numerical values. Usually a specific atom or the corresponding nucleus is denoted by the chemical symbol, which is determined by Z alone, and the value of Z indicated by subscript figures on the left of the symbol with the value of A given by superscript figures on the right. The isotope of elementary oxygen (0) with a nuclear charge $Z = 8$ and an atomic weight of 16 is thus denoted by

$${}_8O^{16}.$$

[2]) In general it is required to compare the mass of Z protons plus N neutrons, i.e. $Z\,M_p + N\,M_n$ with the mass of the atomic nucleus M_k. If however to both is added the mass of Z electrons ($Z\,m_e$), we get since $M_p + m_e = M_H =$ the mass of the hydrogen atom, a comparison between $Z\,M_H + N\,M_n$ and the atomic mass M ($= M_k + Z\,m_e$).

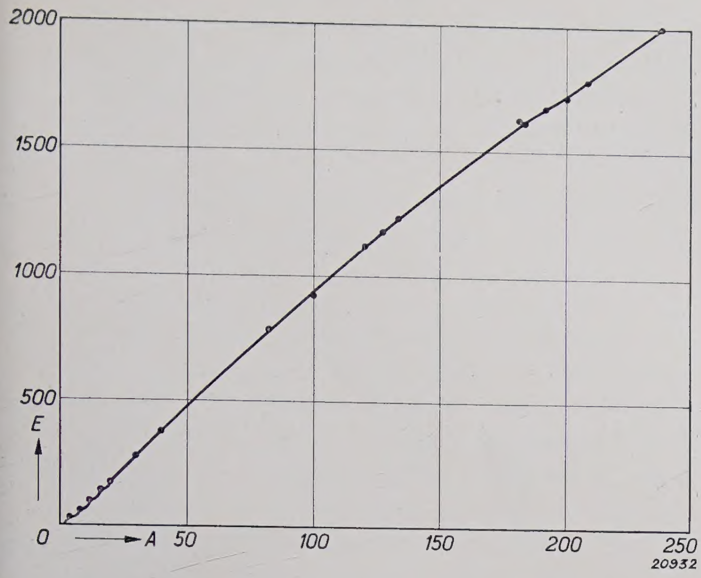

Fig. 2. Binding energy of the nucleus in 0.001 atomic-weight units (a smooth curve is drawn through the points most accurately known).

In *fig. 2* the binding energy of the atomic nuclei is plotted as a function of the mass number, and in *fig. 3* the same values are given for the lightest nuclei ($A < 50$). On the whole the proportionality is fairly good, although for the lightest nuclei there is a distinct oscillation in the curve, the binding energy being a maximum at $A = 4, 8, 12$, etc. Since $A = 4$ is the mass number of the helium atom $_2He^4$, the firm bond in nuclei whose weights are multiples of 4 is regarded as evidence of the

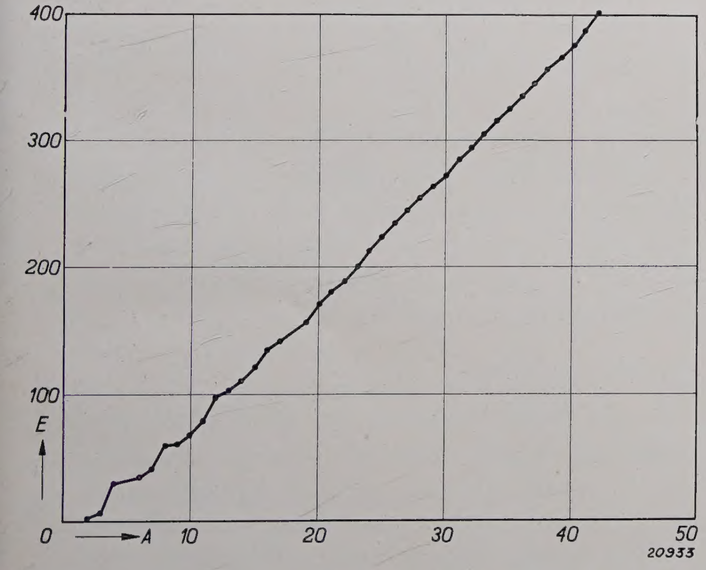

Fig. 3. Binding energy in 0.001 atomic-weight units of light nuclei (up to Ca^{42}). The oscillation may be followed up to $A = 24$.

presence of separate alpha particles in the nuclei.

It may also be asked to what maximum values the binding energy may assume for each elementary particle. This value may be found by dividing the

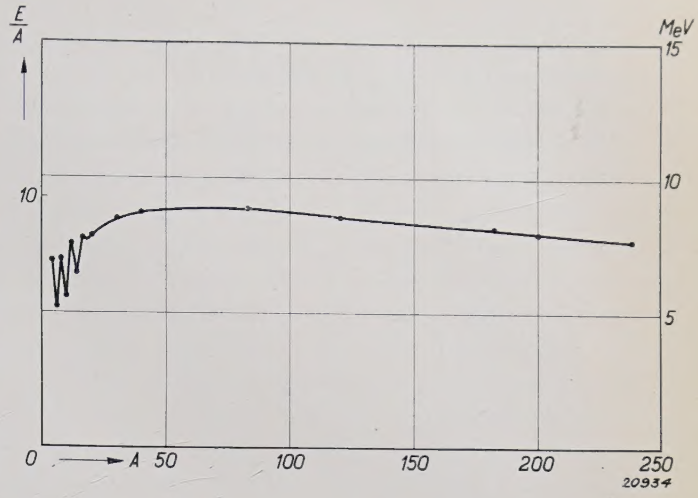

Fig. 4. Binding energy per particle for all nuclei (to left in 0.001 atomic-weight units; to right in MeV). Through the most accurately-known points a smooth curve has been drawn. The oscillation for $A < 20$ is indicated diagrammatically by a zigzag line.

energy given in fig. 3 by A. As shown in *fig. 4* this energy for $A > 20$ is approximately a constant, which already follows from the fact that the curve in fig. 2 is a straight line.

Conception of the Nucleus as a "Liquid Drop"

The constant energy of approximately 0.008 atomic weight units (= 12 μ erg = 7.5 MeV) which is required to expel a single elementary particle (proton or neutron) from the nucleus, has led to the atomic nucleus being compared to a "liquid drop" in view of the analogy between this energy value and a "heat of vaporisation". The application of this conception will be now discussed from various aspects. The comparison of the nucleus to a liquid drop can be developed in considerable detail and is even susceptible to quantitative expression. It postulates, for instance, that the volume of the nucleus is proportional to the "quantity of liquid" i.e. A. The radius of the nucleus, assumed to be spherical, must therefore be proportional to $\sqrt[3]{A}$ or $A^{1/3}$. Estimates made by other methods of the radius of the heavy nucleus actually give to a reasonable approximation a radius of:

$$r = 2.0 \cdot 10^{-13} \cdot A^{1/3} \text{ cm.}$$

In the case of a true liquid drop, the surface tension must be considered in addition to the energy of condensation; the former is an energy magnitude which apparently reduces the condensation energy in proportion to the area of surface. It is, indeed, found that the reduction in energy per elementary particle (*fig. 4*) observed at low values of A can be expressed numerically by a function which is proportional to $A^{2/3}$, i.e. to the square of the radius

or to the surface (this energy per elementary particle is therefore proportional to $A^{-1/3}$, and hence increases with diminishing A). A plausible explanation is also forthcoming for the small downward

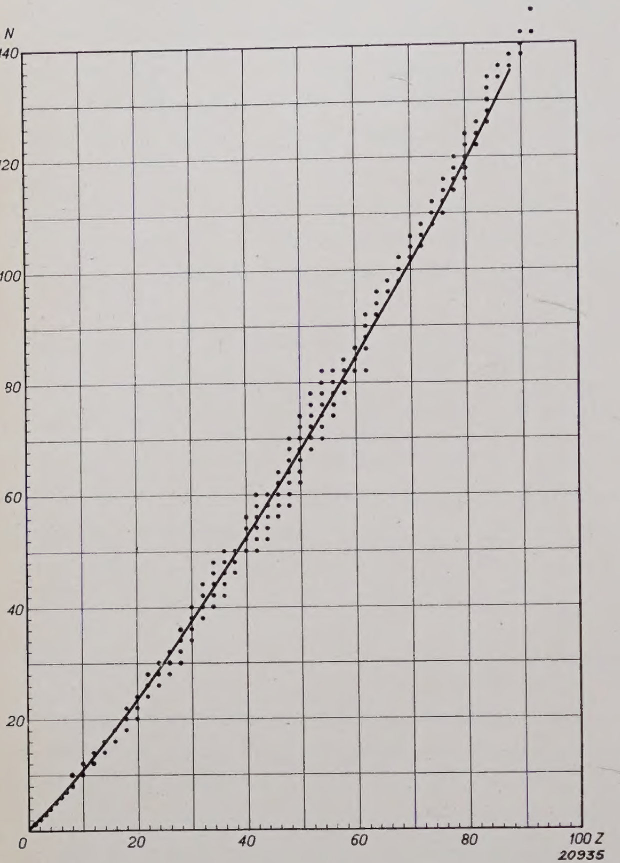

Fig. 5. N-Z diagram for nuclei with even values of A. Above $Z = 7$ only even values of N and Z are obtained. Isobars, i.e. nuclei with identical A values and different Z and N values (· .), are general features; isotopes, i.e. nuclei with identical Z and different A values, are frequent for the higher values of Z.

slope, shown in fig. 4 towards the highest values of A. This is accounted for by the mutual repulsion of the protons, the energy of repulsion being according to Coulomb's law proportional to Z^2/r, i.e. approximately to $A^{5/3}$. For each elementary particle this energy is proportional to $A^{2/3}$, and it increases with rising values of A.

Regarding the ratios of the numbers of protons and neutrons present in different atomic nuclei experience shows that these vary from $N/Z = 1$ for the lightest nuclei to $N/Z =$ approximately 1.5 for the heavy nuclei. In *figs. 5* and *6*, the known atomic nuclei are plotted in a system of co-ordinates according to their N and Z values. Fig. 5 relates to nuclei with even values of A, and fig. 6 to nuclei with odd values of A. The nuclei with even values of A possess as a rule even values of N and Z, as indicated in the figure, while nuclei with odd values of A have an equal number of even and odd values for Z and N. Space does not permit a detailed discussion of the important conclusions which can be drawn from these diagrams regarding the forces operating between the various elementary particles.

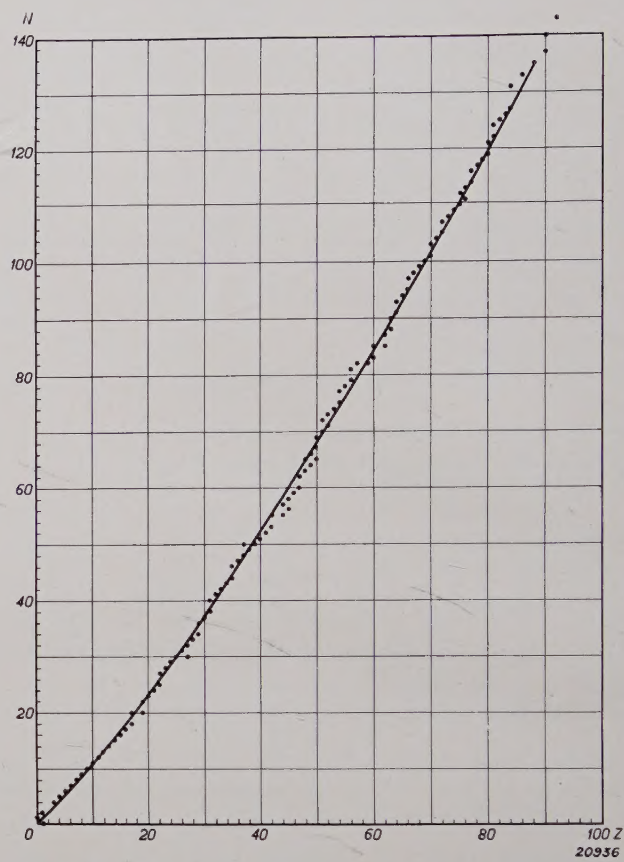

Fig. 6. N-Z diagram for nuclei with odd values of A. Even and odd values of Z are found with equal frequency. Isobars (· .) are rare. The number of isotopes is a maximum of 2 per element.

It must suffice to point out that by far the most powerful binding forces occur between protons and neutrons, and that a weaker bond exists between each pair of neutrons or protons (quite apart from the mutual repulsion between the protons as determined by Coulomb's law).

Nuclear Reactions

A brief survey has been made above of the stable nuclei and their binding energy. We will now discuss the reactions which are possible between atomic nuclei. In general these reactions consist of bombarding a static atomic nucleus (K_1) with a light nucleus which may be termed the projectile (P_1). The following may act as projectiles:

1. The hydrogen nucleus (proton) . . . . $_1H^1$
2. The nucleus of the heavy-hydrogen atom (deuteron) . . . . $_1H^2$
3. The helium nucleus (alpha-particle) . . $_2He^4$
4. The neutron . . . . $_0n^1$

The high velocity of the projectiles is derived from the intrinsic energy contained in radioactive substances or by means of canal or positive rays (positive ions accelerated in a suitable discharge tube).

The liquid drop concept is also of value here in depicting the mechanism of the processes taking place. The projectile P_1 penetrates the nucleus K_1 and forms an intermediate nucleus K_{int} with it. In this intermediate nucleus the particles will however not be in the same state as in a stable nucleus of the same weight. Both the kinetic energy of the projectile and the binding energy liberated are absorbed by this intermediate nucleus. It may be said that the drop has acquired a higher "temperature" and can therefore volatilise more easily, i.e. it tends to emit a projectile P_2. If this secondary projectile is identical with P_1, only a scattering process has taken place. But if P_2 differs from P_1, a nuclear reaction has resulted:

$$P_1 + K_1 \rightarrow K_{int} \rightarrow K_2 + P_2 \,,$$

and a new nucleus K_2 takes the place of the initial K_1. This process is shown schematically in *fig. 7.*

Fig. 7. Diagram of a nuclear reaction resulting on the bombardment of a nucleus K_1 with a projectile P_1, as a result of which an intermediate nucleus K_{int} is produced, which then disintegrates into a new nucleus K_2 and a projectile P_2.

We shall now discuss a few examples of nuclear reactions:

If nitrogen is submitted to bombardment with alpha-particles, high-speed protons will be emitted as a result thereof:

$${}_2He^4 + {}_7N^{14} \rightarrow {}_8O^{17} + {}_1H^1$$

The importance of this reaction is that it was the first transmutation of this type discovered (Rutherford, 1919).

Another well-known reaction is that observed by Cockroft and Walton in 1932 which was initiated by bombarding lithium with high-speed protons (hydrogen positive rays):

$${}_1H^1 + {}_3Li^7 \rightarrow 2\,{}_2He^4.$$

In this case the secondary projectile P_2 was the same as the residual nucleus K_2.

Induced Radio-Activity

As our third example we shall refer to the action of alpha-particles on aluminium, resulting in two reactions taking place simultaneously, viz.:

$${}_2He^4 + {}_{13}Al^{27} \begin{array}{l} \nearrow {}_{14}Si^{30} + {}_1H^1. \\ \searrow {}_{15}P^{30} + {}_0n^1. \end{array}$$

Protons as well as neutrons may occur as secondary projectiles. It is interesting to note that in the second reaction the product ${}_{15}P^{30}$ represents an unstable nucleus which by the emission of an electron (viz., a positive electron or positron) is converted to a stable nucleus with a half-life period of 3.25 min. This was the first case of induced radio-activity and was observed by Irene Joliot-Curie and F. Joliot in 1934. The disintegration of the phosphorus atom takes place according to the following equation:

$${}_{15}P^{30}\,{}^* \rightarrow {}_{14}Si^{30} + e^+.$$

The asterisk * denotes that the product is unstable.

An important series of transmutations are those in which the primary projectile is the nucleus of the heavy-hydrogen atom ${}_1H^2$ (deuteron). These reactions were studied principally by Lawrence, and of which the following is an example:

$${}_1H^2 + {}_{11}Na^{23} \rightarrow {}_1H^1 + {}_{11}Na^{24}\,{}^*.$$

Again here unstable, i.e. radio-active, products are frequently formed. In the case cited above the disintegration process is expressed by:

$${}_{11}Na^{24}\,{}^* \rightarrow {}_{12}\,Mg^{24} + e^-.$$

The sodium nucleus under consideration is therefore a beta-radiator.

Finally, there is an important group of transformations which are initiated by neutrons, the neutrons required for this purpose being generated by one of the two following methods:

1. From a radio-active preparation (alpha-radiator) and beryllium:

$${}_2He^4 + {}_4Be^9 \rightarrow {}_6C^{12} + {}_0n^1.$$

2. By the positive ray method in which lithium, beryllium or compounds of deuterium (D_3PO_4, ND_4Cl) [3]) are bombarded with deuterons.

The following transformations take place:

$${}_1H^2 + {}_1H^2 \rightarrow {}_2He^3 + {}_0n^1,$$
$${}_1H^2 + {}_3Li^7 \rightarrow 2\,{}_2He^4 + {}_0n^1,$$
$${}_1H^2 + {}_4Be^9 \rightarrow {}_5B^{10} + {}_0n^1.$$

Below some typical examples of neutron reactions are given; these have been mainly investigated by Fermi. We have intentionally selected three reactions which give the same end-product:

$${}_0n^1 + {}_{14}Si^{28} \rightarrow {}_{13}Al^{28}\,{}^* + {}_1H^1,$$
$${}_0n^1 + {}_{15}P^{31} \rightarrow {}_{13}Al^{28}\,{}^* + {}_2He^4,$$
$${}_0n^1 + {}_{13}Al^{27} \rightarrow {}_{13}Al^{28}\,{}^*.$$

[3]) D is the common abbreviation for ${}_1H^2$.

The $_{13}Al^{28}$ * disintegrates further according to the equation:

$$_{13}Al^{28} * \rightarrow {}_{14}Si^{28} + e^{-}.$$

The last of these three reactions is of particular interest. This type of process in which no secondary projectile is produced, but the neutron remains bound in the nucleus, is initiated by artificially retarded neutrons, i.e. neutrons which have been passed through a medium rich in protons (e.g. a layer of water or paraffin wax a few cm thick). As a result the neutrons have lost so much energy by collision with hydrogen nuclei that they retain only a small energy of the order of 0.001 to 100 eV in place of an initial energy of several MeV.

Yields from Nuclear Reactions

Brief reference must still be made to the yields from the nuclear reactions discussed above. Since the nuclear diameter is of the order of 10^{-12} cm, it would be expected that the probability of striking the nucleus K_1 (fig. 7) with a projectile P_1 will depend on the effective sectional area per nucleus of 10^{-24} cm². If instead of investigating the yield per atom, we consider the total yield it is necessary to include also the range of the projectiles in the medium in question and the concentration of the nuclei K_1. If the medium contains n nuclei K_1 per cub cm and if the range is R cm, then the yield will be

$$\int_0^R n\ \sigma(x)\ dx.$$

where σ is the effective section at the velocity of the particles at the point in question. This effective section diminishes rapidly with the velocity. In the case of charged projectiles with a low energy the electrical field must also be taken into consideration, as it prevents the (positively) charged particle (proton or alpha-particle) from penetrating the nucleus. The reduction from this cause in the yield of the reaction will be the lower the smaller the charges of P_1 and K_1, which explains why in the reaction investigated by Cockroft and Walton (protons bombarding Li) measurable transmutation was still obtained at exceptionally low voltages (10 keV).

On the other hand, there are other factors which may increase the probability of reaction. In the case of neutrons, for instance, in which the repulsion by the nuclear field may be neglected, the probability of a projectile striking its target may be very high at specific low velocities. We are referring to a resonance phenomenon, where the effective section is in many cases 10000 times the normal target surface of 10^{-24} sq. cm.

Importance of Nuclear Physics in Technology

Nuclear physics has become of importance to technology not only in regard to the need for evolving technical apparatus suitable for investigating the atomic nucleus, such as positive ray tubes with their auxiliary high-tension units (as already indicated at the outset), but also in regard to the future possibility of preparing adequate quantities of artificial radio-active materials for practical use. The applications of these substances will be mainly for medical, biological, chemical and general technological purposes.

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ALTERNATING-CURRENT CIRCUITS FOR DISCHARGE LAMPS

By E. G. DORGELO.

Summary. In contradistinction to the incandescent electric lamp, the gas discharge lamp possesses electrical characteristics which are entirely different for those of an ordinary resistance. Therefore, when calculating the data for a proposed installation of gas discharge lamps modified methods must be employed; these are discussed in some detail in this article. The characteristics of the simplest lamp installation, consisting of a gas discharge lamp with a choke coil connected in series with it, are analysed as an example.

Introduction

A fundamental difference between gas discharge lamps and incandescent electric lamps is that the former must always be connected to the mains supply through a current-limiting device.

In its simplest form this component consists of a series resistance or a choking coil which limits the current passing through the lamp. If the running or starting voltage of the lamp is higher than the mains voltage, a transformer which can be built in with the choke must be inserted in the circuit. A so-called leakage transformer with the same electrical characteristics can also be used in place of the transformer connected in series with a choke.

The current-limiting device not only limits the current intensity but also modifies the character of the current. It is useful to know also the variations in the intensity and character of the current with alteration in the characteristics of the lamp or with fluctuations in mains voltage; a detailed knowledge of the method of operation of the current-limiting device is also desirable to enable its dimensions to be kept small and its manufacture inexpensive.

A brief survey is given below of the principal points which have to be considered in arriving at the electrical specification of discharge lamps and their current-limiting devices; it is also shown how — by adopting certain simplifications — the electrical characteristics of an installation can be calculated. It will be seen that each individual requirement of lamp voltage, power factor, the sensitivity of the lamp to voltage fluctuations, duration of the heating-up period, etc., introduces its own particular set of conditions, which cannot always be satisfied simultaneously, so that frequently a compromise must be made. These

Sodium lamp

Neon lamp

Mercury lamp SP

Mercury lamp HP

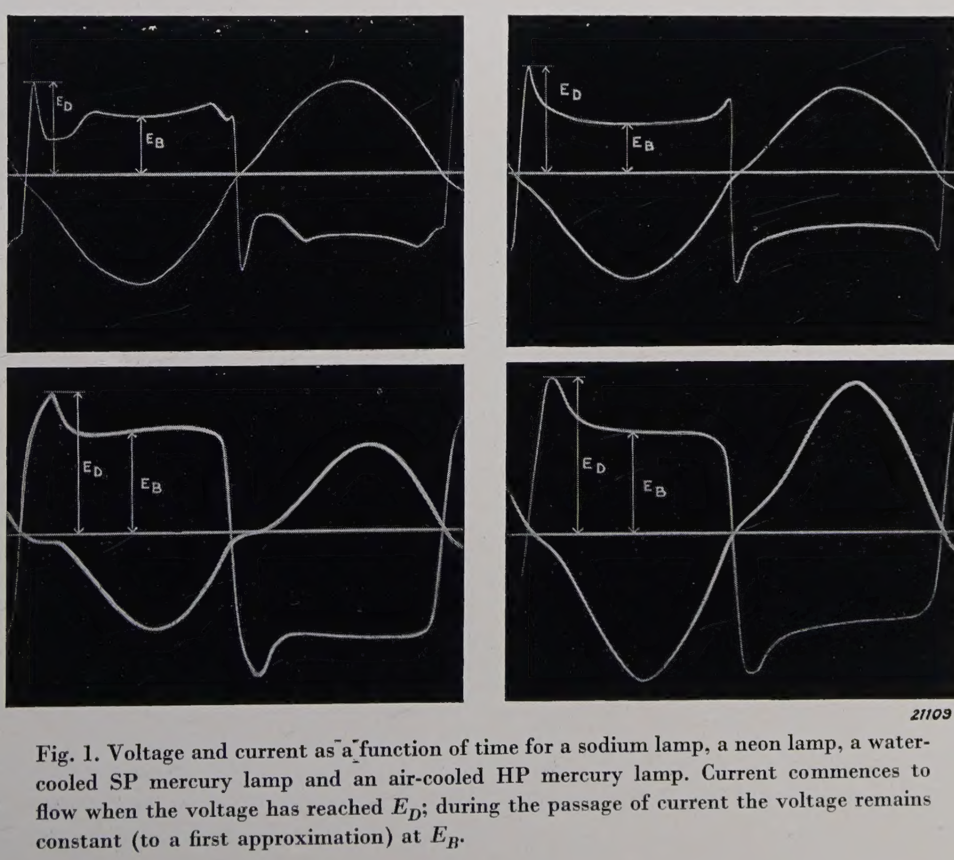


Fig. 1. Voltage and current as a function of time for a sodium lamp, a neon lamp, a water-cooled SP mercury lamp and an air-cooled HP mercury lamp. Current commences to flow when the voltage has reached E_D; during the passage of current the voltage remains constant (to a first approximation) at E_B.

limitations are in part due to the simplicity of the circuit discussed here and which consists of a choke coil in series with the lamp. If, on the other hand, more complex circuits are used, a number of possibilities arise which cannot be discussed in this article.

Mathematical Simplifications

The following simplifications will be taken as the basis of our analysis:

1) The choke coil is assumed to combine a constant self-inductance L with an ohmic resistance R.
2) The mains voltage is assumed to be sinusoidal (with an instantaneous value of $E \sin \omega t$).
3) While the lamp remains burning, the voltage applied to the lamp is taken to be constant (E_B) with the current in opposition to it. To ensure that the lamp burns during each half-cycle, the voltage at its terminals must however first reach a value which is greater than E_B and which will be termed the striking voltage E_D.

The variation in the voltage as a function of the time is plotted in *fig. 1* for sodium, mercury and neon lamps. While the assumption that the running voltage is constant was found to be true in the case of mercury lamps, with sodium lamps on the other hand the oscillogram reveals a diminution of this voltage at the beginning and end of each half-cycle. But for most calculations it was found permissible to ascribe a constant mean value to the running voltage in these cases also.

Final Mains Current and Consumption Current

The inductive circuit described below is shown in diagrammatic form in *fig. 2*. It is assumed that the mains voltage ($E \sin \omega t$) is applied when its

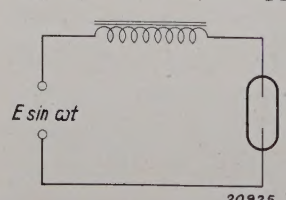


Fig. 2. The circuit under discussion. The lamp and choke coil are connected in series and the mains voltage $E \sin \omega t$ is applied. The choke coil has self-inductance L and resistance R.

instantaneous value is just zero ($\omega t = 0$); no current then passes through the choke coil and the lamp. Only when $E \sin \omega t = E_D$ (which is only possible when $E > E_D$), does ignition take place and a current is able to pass. The lamp thus behaves like a switch which is operated at the moment when $E \sin \omega t = E_D$.

We then have:

$$\omega t = \arc \sin \frac{E_D}{E}.$$

This value of ωt will be denoted by a. If we continue to compare the lamp with a switch, we must also assume that on closing the switch the circuit absorbs an e.m.f. with a value of E_D and a polarity in opposition to the applied mains voltage. *Fig. 3*

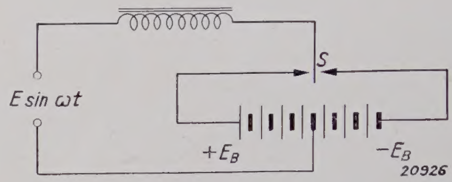


Fig. 3. Equivalent circuit for the lamp. An e.m.f. E_B which can be applied by closing the switch takes the place of the discharge lamp.

shows the equivalent circuit of the lamp described above. Switch S is closed as soon as the absolute value of the voltage exceeds E_D and remains closed until the current changes sign and becomes zero.

The voltage equilibrium obtaining in the equivalent circuit after closing the switch can be expressed by the equation:

$$E \sin \omega t = i R + L \frac{di}{dt} + E_B.$$

Solving this equation for i we get:

$$\left.\begin{aligned} i &= i_s + i_v, \text{ where} \\ i_s &= \frac{E}{Z} \sin(\omega t - \psi) - \frac{E_B}{R}, \\ \text{and } i_v &= \left[\frac{E_B}{R} - \frac{E}{Z} \sin(a - \psi)\right] e^{\frac{R}{\omega L}(a - \omega t)}. \end{aligned}\right\} \quad (1)$$

Here

$$Z = \sqrt{R^2 + (\omega L)^2} \text{ (total impedance)},$$

$$\psi = \arc \tan \frac{\omega L}{R}.$$

If in the equivalent circuit (fig. 3) the switch were kept closed for any arbitrarily long period, the current intensity i_v would become very small after a certain time ($\lim i_v = 0$). The current then flowing is given by:

$$i_{t=\infty} = i_s = \frac{E}{Z} \sin(\omega t - \psi) - \frac{E_B}{R}.$$

i_s is therefore termed the final current. As may be seen i_s is compounded of an A.C. component given by the mains voltage divided by the impedance of

the circuit, and a D.C. component determined by the direct voltage E_B and the resistance R.

At the moment of closing the circuit ($\omega t = \alpha$), i_s will as a rule not become zero immediately. In this case the compensation current i_v ensures that no resultant current flows when the circuit is closed. Circuits are frequently encountered in electricity in which the circuit-closing phenomena occurring are of a transient nature. This is however not the case with gas discharges. Ignition is repeated twice in each cycle and the circuit-closing phenomena here have a continuous effect on the current curve, as will be further shown below.

Periodical Ignition and Extinction

As already indicated the switch S in the equivalent circuit (fig. 3) is opened the instant the current becomes zero ($\omega t = \beta$). It is shown in *fig. 4* that

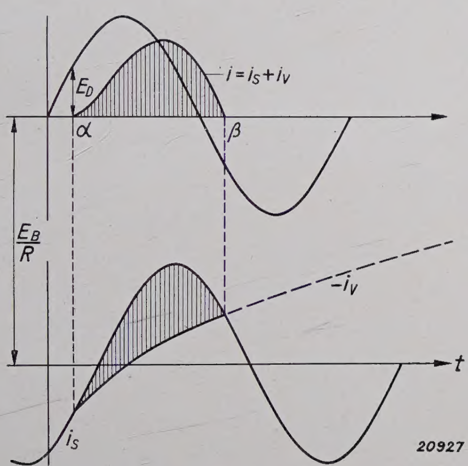


Fig. 4. Current intensity through the lamp. The final mains current derived from the mains voltage $E \sin \omega t$ and the impedance Z is represented by:

$$i_s = \frac{E}{Z} \sin (\omega t - \psi) - \frac{E_B}{R}$$

and the compensation current by:

$$i_v = \left[\frac{E_B}{R} - \frac{E}{Z} \sin (\alpha - \psi)\right] e^{\frac{R}{\omega L}(\alpha - \omega t)}$$

The hatched ordinates between the curves i_s and i_v represents the current intensity i. In the case illustrated the discharge period is exactly half a cycle ($\beta = \alpha + \pi$).

the current rapidly becomes zero, in fact so quickly that no marked diminution in i_v as yet takes place. When the current has once become zero, it remains at this value until the absolute value of the mains voltage has again attained the value E_D. During this interval, which may be termed the re-ignition interval δ, not only is $i = 0$ but also $di/dt = 0$. The only voltage remaining is then the mains voltage and it also determines the instant of re-ignition. In general the polarity of the mains voltage is then reversed; after re-ignition we can again make use of our equivalent circuit diagram, although now the switch must be closed in the opposite direction.

It is evident that the expression which we now obtain for the current again contains the two components i_s and i_v. i_v is again determined by the condition that at the instant of re-ignition $i = 0$. Hence contrary to circuits which do not contain a discharge lamp, the compensation current never entirely disappears here. It is this component which gives the current a permanent, non-sinusoidal character.

If the voltage E_D at which the lamp commences to burn is constant, re-ignition occurs when $\omega t = \alpha$, $\alpha + \pi$, $\alpha + 2\pi$, etc. The expressions for i_s and i_v are the same in all half-cycles, apart from the sign. To determine the character of the current it is therefore sufficient to consider a single half-cycle.

Discharge Interval and Dark Interval

We shall now return to equation (1). To simplify further analysis it will be assumed that R can be neglected with reference to ωL. The equation giving the current can then be derived from equation (1) by expanding the power function as a series, so that at the limit $R \rightarrow 0$ only the first two terms remain. We then get:

$$i = \frac{1}{\omega L} \left[E (\cos \alpha - \cos \omega t) + E_B(\alpha - \omega t)\right]. \quad (2)$$

By calculation or by means of the construction shown in *fig. 5*, the instant ($\omega t = \beta$) can then be determined at which i becomes zero for the first time. Fig. 5 shows that the value of β is determined by E_D and E_B and that the discharge interval ($\beta - \alpha$) can be both longer and shorter than a half-cycle.

If $\beta - \alpha < \pi$ the current will remain zero for a finite interval after extinction has taken place

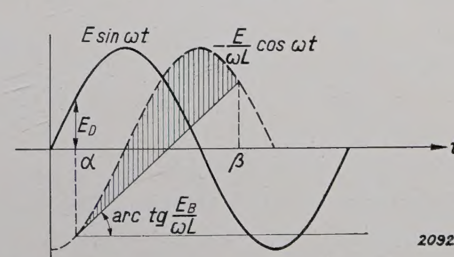


Fig. 5. The same diagram as fig. 4, but for $R = 0$, i.e. $Z = \omega L$. The e-function is resolved into a straight line with the slope $E_B/\omega L$.

and until re-ignition of the lamp takes place in the opposite direction. The dark interval is given by $\delta = \pi - (\beta - \alpha)$. Except for their algebraical

signs the voltages and currents are exactly the same in the second half-cycle as in the first.

If $\beta - \alpha = \pi$, the dark interval disappears, as is generally desirable, since the lamp radiates very little light during this period and will be subject to much less flickering when the dark interval is eliminated.

Consider now the case when $\beta - \alpha > \pi$. It is seen that in this case also the lamp is immediately re-ignited in the opposite direction after extinction. The voltage at the instant re-ignition takes place is now greater than E_D in the negative phase, while in the positive phase the voltage is exactly equal to E_D. The characters of the two phases are therefore not identical. *Fig. 6* shows a sequence of half-cycles where it is apparent that the positive phase is longer and the negative phase shorter than a half-cycle. The sum of a positive and a negative phase is however slightly longer than a whole cycle, so that the variation of the current is not

$$\omega t = \beta \leqslant \pi + \alpha,$$

where the sign of equality applies when the dark interval is zero. On inserting this value of ωt in equation (2) we get:

$$\cos \alpha \leqslant \frac{\pi}{2} \frac{E_B}{E}, \quad \ldots \ldots \quad (3)$$

the sign of equality again applying to the absence of a dark interval.

The voltage E_s at the instant of re-ignition however satisfies the following equation which can be readily deduced from fig. 6:

$$\sin \alpha = \frac{E_S}{E} \geqslant \frac{E_D}{E}, \quad \ldots \ldots \quad (4)$$

where the sign of equality now implies the existence of a dark interval, i.e. for just the converse case to that for which equation (3) is valid. We thus arrive at the following scheme:

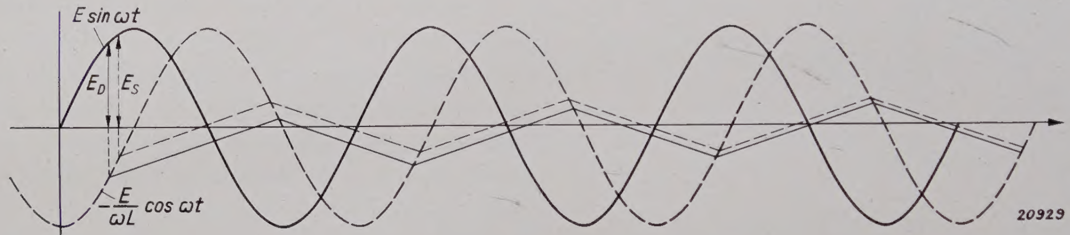


Fig. 6. The same diagram as fig. 5, but expanded to a number of periods. If the first discharge lasts longer than a half-cycle (full line) the third discharge will be shorter than the first, the fifth shorter than the third, and so on. The full line gradually approaches the dash line which represents the equilibrium condition in which the duration of the discharge is exactly half a cycle. At this equilibrium the voltage E_s available for re-ignition is greater than E_D.

periodic. As shown in the figure, the times of ignition are displaced progressively such that the equilibrium condition indicated by the dash line is attained. In this state the two half-phases are identical and are equal to a half-cycle. The voltage E at the instant of re-ignition is the same for both half-cycles in this equilibrium condition and is greater than the striking voltage E_D.

We thus arrive at the conclusions that the mains voltage may exceed the striking voltage at the instant the lamp is re-ignited. The excess value of the mains voltage is a measure of the reliability of re-ignition.

It is therefore important to know whether at given values of E_B, E_D and E the dark interval can be zero or not. The criterion for this is determined as follows.

Substituting $\omega t = \alpha$ in equation (2), we get as required $i = 0$. At the instant $\omega t = \beta$ where again $i = 0$ we get for the equilibrium state:

With interval	Interval just zero	No interval
$\sin \alpha = \frac{E_D}{E}$	$\sin \alpha = \frac{E_D}{E}$	$\sin \alpha > \frac{E_D}{E}$
$\cos \alpha = \frac{\pi}{2} \frac{E_B}{E}$	$\cos \alpha = \frac{\pi}{2} \frac{E_B}{E}$	$\cos \alpha < \frac{\pi}{2} \frac{E_B}{E}$
$\left(\frac{\pi}{2} \frac{E_B}{E}\right)^2 + \left(\frac{E_D}{E}\right)^2 > 1$	$\left(\frac{\pi}{2} \frac{E_B}{E}\right)^2 + \left(\frac{E_D}{E}\right)^2 = 1$	$\left(\frac{\pi}{2} \frac{E_B}{E}\right)^2 + \left(\frac{E_D}{E}\right)^2 < 1$

The third line in this table is obtained by squaring and adding the first two equations. It is found that the following expression may be taken as the criterion for immediate re-ignition:

$$\left(\frac{\pi}{2} \cdot \frac{E_B}{E}\right)^2 + \left(\frac{E_D}{E}\right)^2 \leqslant 1 \quad \ldots \quad (5)$$

If the sign of equality applies, then α is determined both by the discharge interval given by equation (3)

and by the dark interval given by equation (4); where the sign $<$ applies, a is determined by the discharge interval alone, when $E \sin a > E_D$, and the difference $E \sin a - E_D$ may be taken as a measure for the reliability of re-ignition.

Reliability of Re-ignition and Power Factor

It is interesting to examine what cases arise when E_B and E_D vary from 0 to E either together or independently of each other.

This variation can in fact be examined in the case of a mercury lamp, for on heating the lamp the pressure of the mercury increases and hence also the values of E_B and E_D.

At very low values of E_B/E and E_D/E, equation (5) is definitely satisfied. It follows from equation (3) that a is approximately 90 deg [1]). Ignition therefore takes place when the mains voltage has almost reached its peak value. The reliability is therefore very high.

If E_B and E_D increase, equation (3) indicates that a diminishes. Ignition is therefore obtained relatively earlier. The amount by which the mains voltage exceeds E_D is gradually reduced and eventually becomes zero (*fig.* 7). On further raising E_B and E_D, a must again increase, and the instant of ignition is then no longer given by equation (3) but by equation (4), at the same time a dark interval is obtained. We have thus passed through the minimum value of a. How small a can be made depends on the ratio E_D/E_B, i.e. merely on the lamp.

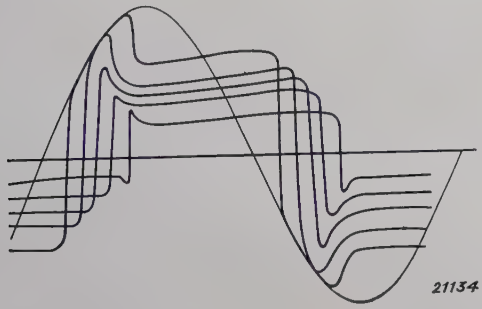


Fig. 7. This diagram is based on oscillograms recording the variation of the electrode voltage of a mercury lamp. The five exposures were made at short intervals during the heating-up of the lamp. The gradual increase in the striking and running voltages is indicated as well as the resulting displacement of the moment of ignition. In the case of an air-cooled mercury lamp this increase ceases before the striking voltage becomes greater than the mains voltage at the moment of extinction. In the case of a water-cooled mercury lamp with which the above diagram was obtained, heating-up continues after the mains voltage is reached. A dark interval occurs, during which the voltage impressed on the lamp is exactly equal to the mains voltage.

[1]) An extreme case occurs when the lamp is short circuited; the current then passes through zero at the instant the mains voltage just passes through its peak value.

If, for instance $E_D/E_B = 1$, then it follows from equation (5):

$$\left[\left(\frac{\pi}{2}\right)^2 + 1\right]\left(\frac{E_B}{E}\right)^2 = 1.$$

Hence $E_B/E = 0.536$ and $(\cos a)_{\max} = 0.536 \cdot \pi/2 = 0.84$. With a higher ratio of E_D/E_B the maximum value which $\cos a$ can assume is naturally lower.

The greater the value of $\cos a$ the smaller will be the phase displacement between the current and the mains voltage, in so far as one can speak of a phase displacement in the case of a non-sinusoidal current. It may therefore be expected that there is a close relationship between the instant of ignition and the power factor. For a sinusoidal current the power factor is usually given as $\cos \varphi$, which we define as the ratio of the true power to the wattless or apparent power.

Limiting consideration to the case where the dark interval is zero, the power W is equal to the running voltage multiplied by the mean current intensity during a half-cycle:

$$W = E_B \cdot \frac{1}{\pi} \int_a^{a+\pi} i \, d(\omega t).$$

By means of equation (2) we can solve the integral and thus get:

$$W = E_B \frac{\frac{2}{\pi}\sqrt{E^2 - \left(\frac{\pi}{2} E_B\right)^2}}{\omega L}.$$

Inserting the effective value (E_{eff}) of the mains voltage, we have:

$$W = E_B \cdot \frac{0.9 \sqrt{E_{eff}^2 - (1.11 \, E_B)^2}}{\omega L} \quad . \; . \; (6)$$

The apparent power VA can be calculated in the same way, thus:

$$VA = E_{eff} \cdot i_{eff} = E_{eff} \cdot \sqrt{\frac{1}{\pi} \int_a^{a+\pi} i^2 \, d(\omega t)}.$$

and we get the expression:

$$VA = E_{eff} \cdot \frac{\sqrt{E_{eff} - (1.09 \, E_B)^2}}{\omega L} \quad . \; . \; (7)$$

As the terms under the root signs in (6) and (7) are almost the same, we have for the power factor η to a first approximation:

$$\eta = \frac{W}{VA} = 0.9 \cdot \frac{E_B}{E_{eff}} = 0.81 \cos a.$$

In this circuit therefore the ratio of the running

voltage of the lamp to the effective mains voltage is a measure of the power factor.

In the case discussed above where the maximum value of $\cos \alpha$ is realised, the maximum power factor is also obtained, but is only 0.68. It has indeed not been found possible to obtain a higher value with the inductive circuit. Generally E_D/E_B is greater than 1, which results in a still lower power factor. The power factor can be improved by connecting a condenser, which compensates the wattless current component, in parallel with the lamp and choke coil.

Choice of Running Voltage

When designing the combination consisting of the discharge lamp and the current limiting unit, the first point to be determined is the voltage which has to be applied to the lamp and choke coil. A preference is usually shown for direct connection to the mains (e.g. 220 volts for HO-mercury lamps). Other lamps can be run with better efficiency on higher voltages, in which case the mains voltage must be stepped up by transformation (e.g. 440 volts for SO-sodium lamps, 600 volts for water-cooled SP-mercury lamps). To obtain a maximum power factor the running voltage is taken as high as possible for a specific mains voltage (when also the dimensions of the choke coil are reduced to a minimum).

Hitherto we have regarded the striking voltage E_D as having a fixed value, being determined by the characteristics of the lamp. Actually this is not the case, for with all discharge lamps the voltage required for re-ignition increases during the dark interval, as indicated in *fig. 8* by the three thin

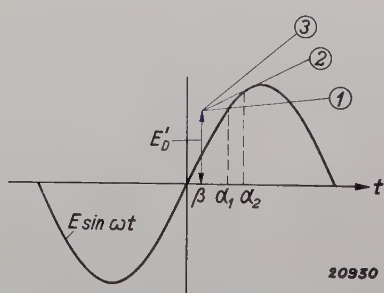


Fig. 8. In the example shown here the mains voltage at the instant β is smaller than the voltage E_D required for re-ignition. It is therefore necessary to wait until the mains voltage has reached this value. In general the voltage required for ignition increases during this interval. *1*, *2* and *3* represent points at which the mains voltage eventually predominates and starts the discharge, while in *3* this does not occur and no re-ignition results.

lines. It may then occur that the instantaneous value of the mains voltage, which at the beginning of the dark interval is smaller than E_D, does not increase sufficiently quickly to attain the voltage required for re-ignition, so that no re-ignition at all takes place (fig. 8, case 3). To prevent this happening the running and striking voltages of the lamp must not be made too high, so that condition (5) specifying the absence of a dark interval down to zero is satisfied.

Stability with respect to Fluctuations in Mains Voltage

The question of determining the lamp voltage has been discussed in principle above; there are however a number of other factors which necessitate a modification of the results arrived at.

The chief of these is a fluctuation in the mains voltage. With slow fluctuations the temperature of the lamp also may change, which in mercury lamps result in an alteration in the striking voltage. The variation of the latter is in the same sense as the fluctuations in mains voltage (the static characteristic is positive); with sodium lamps these variations are in opposite directions, If, for instance, the mains voltage drops, the striking voltage will rise, whereby re-ignition becomes less reliable. In this case the running voltage must therefore be taken lower than required by equation (5) in order to preserve full reliability in service.

On sudden variations in the mains voltage the running voltage may vary also in the opposite direction with mercury lamps (negative dynamic characteristic), so that again here it must be put slightly lower. Fluctuations in mains voltage affect also the consumption of energy and hence the luminous flux. By differentiating equation (6) (at constant E_B) with respect to E_{eff} we get for the percentage variation of the power input:

$$\frac{dW}{W} = \frac{1}{1 - \left(1.11 \frac{E_B}{E}\right)^2} \cdot \frac{d\,E_{eff}}{E_{eff}} \,.$$

The percentage variation in power is therefore always greater than the percentage variation in the mains voltage, the difference being the greater the greater E_B/E. If a considerable fluctuation in W is to be avoided, then according to the last equation, E_B/E must be made too high. This again leads to the condition that the running voltage of the lamp should not be taken too high.

Special importance attaches to the value of the power absorbed with variation in the running voltage. With both mercury and sodium lamps, there is a tendency for the running voltage to increase with the time the lamp has been in use,

This may result in a reduction in power consumption, in other words an increased reduction in the luminous flux; there is, however, also the possibility that the power consumption may also increase and the reduction in light referred to is then either partially or totally compensated.

It follows from equation (6) that with an increase of E_B from 0 to E_{eff}, ω at first increases, and later begins to diminish again. The maximum value is obtained at $E_B = 0.64\ E_{eff}$.

If, for instance, $E_{eff} = 220$ V, the power consumption will increase with the age of the lamp for E_B below 140 volts, while it will diminsh for E_B above 140 volts [2]).

Heating-up of High-Pressure Mercury Lamps

In conclusion reference must be made to the heating-up of mercury lamps. After switching on a certain time must elapse before the voltage across the mercury lamp has reached its full value (10 to 15 mins with an HP lamp, $^1/_2$ to 2 secs with a watercooled SP lamp).

[2]) If E_D is greater than 1.57 E_B, then for $E_B = 0.64\ E_{eff}$ the condition that no dark interval shall occur is no longer satisfied. Extending our analysis to include this case, we should get in place of equation (6) a generalised expression for the power containing an independent variable in addition to E_B and E_D. This aspect of the subject cannot be further pursued here.

As already pointed out in a previous article [3]), a minimum starting current is required for heating-up the lamp, which is two to three times the normal lamp current. The starting current is roughly equal to the short-circuit current i_k of the current-limiting component:

$$i_k = \frac{E_{eff}}{L\omega},$$

while the normal running current is:

$$i = \frac{\sqrt{E_{eff}^2 - (1.09\ E_B)^2}}{\omega L}.$$

For i_k greater than 2 i, we have $E_B > 0.79\ E_{eff}$, thus giving in this case a minimum running voltage, which is so high that it conflicts with the requirements set out above. This difficulty may be overcome by using a choke coil during the heating-up period with a lower self-inductance than required for normal running. A method in general use for this purpose provides a fairly high saturation of the iron in the series connected choking coil. The self-inductance then diminishes with increase in the current intensity, such that the short-circuit current i_k does actually reduce the impedance of the choke.

[3]) Philips techn. Rev., 1, 129, 1936.

PUBLIC LIGHTING. PRINCIPLES OF ROAD LIGHTING

By G. B. VAN DE WERFHORST.

Introduction

Under the term public lighting we shall include in the present article every class of permanent lighting installation on public highways, squares, roads, bridges, viaducts and subways, provided essentially for the convenience of road traffic as distinct from water-borne and railway traffic.

There is by no means a consensus of opinion in regard to the principles of road lighting and their practical applications. This divergence of opinion cannot occasion surprise when it is remembered that in practically all countries the provision of public lighting is left in the hands of local authorities, each of which has adopted an individual policy not in harmony with those of other bodies. The latitude in this direction is due to the absence of uniform official regulations and the lack of universally accepted standards to act as a guide in developing a public lighting scheme. Furthermore, at one place the responsible official is the power-station engineer, and at others either the municipal architect, the traffic inspector or the local surveyor.

Nevertheless, a marked similarity may yet be observed in certain directions. These points of agreement in public lighting schemes may be summarised as follows:

Of the luminous flux provided by the public lighting in all countries at least 30 per cent is directed upwards into the sky.

The appearance of the lighting unit during the day is considered to be more important than the illumination furnished by night; this is well exemplified by the acanthus leaves on gas lamp standards, by the crosier-like ornamentation of lamp standards on esplanades, and the concrete and cast-iron pediments of modern lamp standards and masts.

In the majority of public lighting schemes the lamp standards are only 13 to 16 ft. high, this mounting height having been adopted without alteration from the early oil lamps for which from the considerations of convenience and weight the length of the lamplighter's pole was limited to about 16 ft.

In the present article the endeavour is made to arrive at consistent and rational principles of public lighting shorn of all subordinate considerations and antiquated conceptions.

In the first place, it must be accepted as a general postulate that public lighting constitutes a part of the totality of exterior illumination and that its efficiency and utility to the road user is in many cases closely determined by the other sources of exterior illumination available.

Exterior lighting irrespective of its actual nature may be divided into two groups on the basis of its general type:

a) The lighting is designed to illuminate the surroundings so that the user can discriminate these surroundings; to the road user the surroundings are of principal interest, and the lighting unit itself of secondary importance;
b) The illuminant is designed to attract the attention of the road user and provide him with a signal; in this case the surroundings which may happen to be illuminated at the same time are of secondary interest, and principal importance attaches to the lamp itself, i.e. to the radiation which it directs on the eye of the road user.

An entirely different classification is obtained if lighting systems are classified according to their functions:

c) Lamps which are provided generally for the convenience, benefit, needs, safety, and pleasure of road users; the interests of the general public are here of primary consideration.
d) Lamps installed for the private convenience, safety and advantage of those installing them; private or personal considerations here take first place.

Comparing the classification into a and b with that into c and d, the practice of road lighting gives the following subdivision:

The lighting of streets *per se* with all crossings and viaducts, etc., i.e. illumination in the public interest (function c), where principal importance pertains to the illuminated surroundings and not to the lamps (type a);

Illuminated signals, including those in use on railways, in navigation and on public highways, and on highways embracing vehicle lighting, traffic signals and indications, again always in the public interest (function c), where the lamps and not the surrounding commands first consideration (type b);

Publicity lighting and illuminated signs, irrespective of type, clearly installed for private interests

(function d) and usually so installed that the light source must be viewed directly (type b).

Private lighting, i.e. the lighting of factory premises and areas, vehicle headlights for the personal convenience of drivers, the illumination of drives and entrances to buildings lying back from the highway; these private lighting arrangements are installed for private use (function d), but at times may also operate in the public interest; the design of these lighting installations is extremely diverse (both types a and b, also frequently combined).

These divergent types of external illumination with all their contradictory requirements are found side by side, a juxtaposition which compels an order of priority to be determined. Without such specified priority, it is impossible to realise the desired results or to evaluate the efficiency of a given scheme of exterior illumination and particularly of a scheme of public lighting, in view of interaction between the various intrinsically different lighting schemes.

We shall assume that the public interest has precedence over purely private considerations, and that also where the public interest has alone to be served, safety and benefit shall be given priority over convenience and artistic effects, and that finally other things being equal, a disadvantage to one class of road user shall receive prior consideration over the advantages of another class.

The demands which are made, whether rightly or wrongly, on different public lighting systems differ so markedly that they do not fall exclusively within one or other of the subdivisions in the above classification. Thus the requirements in built-up municipal and urban areas differ so much from those ruling in country districts, that a discussion of public lighting must give adequate consideration to this difference.

In the present article we shall therefore confine ourselves to the public lighting of country roads (class I, II and III roads [1])) outside of built-up town areas, the illumination of which may be generally described as "road lighting". We will first analyse the conditions on class I roads.

Class I Roads

The lighting of class I roads is provided in the public interest. If the question is asked what in these cases is the public interest it will be found that:

Fast automobile traffic is the principal factor to be considered; that it should be possible to travel at speeds of up to 50 m.p.h. is not an undue requirement:

Bicycle traffic is an important factor in some countries where no separate cycling lanes are provided alongside the main highway;

Slow-moving vehicles (handcars and horse-drawn vehicles) if not prohibited from using this class of road must also be given special consideration.

Pedestrian traffic can be neglected.

The public interest requires that traffic should be able to proceed with reasonable safety under the conditions ruling on the highway. To arrive at this factor of safety a specific visibility is necessary which must be provided by the road lighting. How the lighting scheme must be devised and installed to afford satisfactory visibility on a class I road is determined by this need for adequate visibility and in the case under discussion is the sole determinant, since:

Aesthetic aspects bearing on the surrounding landscape are not being considered (on the other hand, in built-up areas the contours of surrounding buildings are important factors);

There is less likelihood of interference from light sources extraneous to the road, so that their existence can be neglected when planning the lighting scheme (in built-up areas entirely different conditions again obtain).;

No consideration need be given to the pleasing appearance of objects on the road, since the question of safety alone has absolute priority (as opposed, for instance, to the requirements of the lighting on esplanades and promenades).

There can be no question of depending on the lighting equipment of vehicles to provide adequate illumination of the highway, for the reason, among others, that however efficient this illumination may be it will inconvenience road users travelling in the opposite direction to such an extent that safe driving is impossible; this policy would therefore be against the condition of prior consideration stated above as well as contravene the need for maximum safety. Roads on which it is sought to avoid the danger inherent in dazzle produced by the headlights of approaching vehicles by providing two traffic lanes have not been sufficiently long in use to enable any definitive conclusions to be drawn [2]).

It is evident therefore that the road must be illuminated by means of permanent lighting units.

[1]) Which country roads outside built-up areas rank as class I, II and III roads depends, *inter alia*, on the regulations in force in each country.

[2]) Cf. van de Werfhorst, De Auto, Sept. 26, 1935: Enkele en dubbele wegen en hunne verlichting.

Since fast motor traffic is the determining factor, we must determine under what conditions the visibility of surrounding objects is sufficient to meet the needs of the average motorist. Economic considerations compel us to adopt the technical solution of the problem which will satisfy the minimum requirements.

Perception of an object on a road takes place either through the centre of the eye: foveal vision, or through a point outside of the centre: peripheral vision. An object is first consciously observed when we look in its direction, i.e. when the eyes are directed towards it and foveal vision is obtained. Whether we actually recognise the object in doing so depends on the definition of the object and this again on the conditions of illumination.

In this connection the two following points must be kept in mind: The eyes of a motorist when travelling at a high speed are directed far to the front (Baart de la Faille, van Lennep [3])), and are not rigidly fixed, but move up and down and to the left and right through a small visual angle. The field of vision of the driver therefore contains only a small cone in which foveal vision is maintained continuously [4]), yet at times his eyes are now and again directed to the nearer field, although continuing to look straight ahead, so that all objects outside the foveal cone of vision are viewed peripherally. Nextly, the question arises in how far we can stipulate that recognition must accompany perception of an object on the road irrespective of the nature of the object.

At a speed of about 50 m.p.h. the average driver focusses his eyes on a point at least 300 to 400 yards in front of his vehicle, provided the conditions of illumination of the field of vision permit. If the eye is focussed on a nearer point the road surface and curb appear with too high a relative velocity. The road surface close to the vehicle becomes converted into a swiftly moving band passing along and under the car; concentration of the eyes in this direction of vision then becomes very fatiguing. It is evident that such concentration is opposed to safety to driving, and the eye must therefore be focussed to a further point if safety is to be assured [5]). The field of vision thus covers only that portion of the road situated at a distance of 300 to 400 yards and even further in front of the vehicle. All objects within a distance of 300 yards are viewed peripherally unless they are accidentally located in the small foveal cone. In the case of peripheral vision alone, there can be no question of the conscious recognition of an object; moreover when the object is within the cone of vision and less than 300 yards away recognition will usually not take place immediately.

At moderate speeds a driver must carry out four to six operations almost simultaneously; the average person can perform only two operations consciously at the same time, so that with a good driver the majority of his reactions must take place automatically.

If an object appears in the field of vision at a distance of 300 to 400 yards or more, it is sufficient for the driver to become aware that some obstacle is located on the road at the point in question. Recognition of the actual nature of the object is not essential in the first instance, for 14 to 18 seconds must still elapse before he reaches the object, i.e. more than sufficient time for performing his subconscious manipulations, whilst his conscious vision is removed from the distant field of vision and focussed entirely on the approaching object in order to be able to recognise it within a distance of 300 yards.

Entirely different conditions arise when peripheral vision operates within a distance of 300 yards and an obstruction suddenly appears within the field of vision and the driver has his eye focussed on a point more than 300 yards away.

It is fortunate that a very weak stimulus in peripheral vision is already sufficient to cause the eye by reflex action to be directed immediately on the point from which the stimulus emanates. Yet just because a weak stimulus is already sufficient to do this, the lack of a peripheral stimulus leads to the unconscious conclusion that no obstruction is present. This alone is sufficient to indicate the extreme danger of lighting a class I road in such a way that only the road surface is illuminated. By installing lamps of special design, frequently with suitable reflectors, it is attemped to distribute the luminous flux of the lamps almost wholly over the road surface in a longitudinal direction. This method results in the more efficient utilisation of the luminous flux generated, practically none being "lost" in the lateral direction, and enables lamp standards to be placed at greater intervals, etc., apparently a decided economic argument although the cost of the lighting units or lamps themselves is high. But it should be remembered that it is not the function of the lighting to give the road

[3]) Cf., *inter alia*, Mededeelingen van de Nederl. Stichting voor Psychotechniek, No. 1.

[4]) Regarding the mechanism of ocular vision, see Bouma, Philips Techn. Rev., 1, 102, 1936.

[5]) Attempts to overtake a vehicle in front is due to the obstructive sensation referred to here. Cf. also van Lennep, footnote 3.

surface a pleasing appearance, but to provide a degree of visibility which will contribute to safety. From road edges which are left dark in an installation of this type the road user does not receive a single stimulus, and — we repeat — this leads to the unconscious and extremely dangerous conclusion that no obstacle may arise from these boundaries. Illumination of the curbs and pathways skirting the highway is not a waste of light, but on the other hand an indispensable necessity.

In addition to the rapid response to weak peripheral stimuli, the complex optical system of the eye also possesses the remarkable ability of not registering any sensation due to an apparently useless stimulus. The same also applies to many stimuli in peripheral vision. This is a fortunate circumstance, for otherwise we would have to determine the sequence with which the eye moving continuously and rapidly sweeps over the whole field of vision. All stimuli which we recognise and nevertheless have not to register are simply neglected. These considerations lead to the rejection of another, unfortunately frequently-used, method of road lighting. Many highways are still illuminated with unscreened lamps at distances of 60 and 70 yards at a mounting height of 16 to 20 feet. As a result of glare from the lamps, a driver travelling along a road illuminated in this way observes on passing each lamp dark patches appearing and disappearing alongside the traffic lane [6]), not in the form of true shadow produced by a material object but as ill-defined dark spots continually changing in shape. A driver knowing this type of road knows from experience that these evanescent peripheral stimuli following in quick succession are only the play of shadows and are not produced by actual obstructions. Unconsciously he suppresses all reaction to these stimuli; he removes them from his visual faculties. But if such a shadow is suddenly produced by an actual obstruction, the resulting stimulus makes just as little impression on the experienced driver; his necessarily automatic operations are performed just as if the obstruction were absent. The collision which then usually occurs is, however, not due to irresponsible and extremely careless driving", in the words of the courts, but to the deceptive illumination provided, which is the more deceptive the greater the experience possessed by the driver and the better he knows the road.

The peripheral area up to a distance of 300 yards in front of the vehicle must therefore be so illuminated that each obstacle produces a perceptible stimulus; in addition the illumination of the whole field of vision must be so devised that no disturbing elements are present within it which are liable to result in a false interpretation of the shadows or react to the detriment of visibility. Moreover the lighting must provide the driver with adequate means of foveal vision as soon as a peripheral stimulus has attracted his attention. In contradistinction to the more distant field just referred to, the rate of perception and recognision of the observed object are here important factors.

How these requirements can be met for both the near and distant fields of vision is beyond the scope of the present article. Nevertheless we may already conclude that the lighting of class I roads entirely falls within the first subhead of the above classification: The lighting of the road itself with its immediate boundaries is the main consideration, the type of lamp a secondary matter, even to the extent that it is desirable to make it as inconspicuous as possible. This method of lighting possesses none of the characteristics of light signals or indicators. The public interest preponderates to such an extent that all illuminated signs or private lighting units must take second place to the road lighting scheme. If the maximum efficiency attainable with this lighting is reduced by vehicle lamps (cycle lamps, or too bright head-lamps of approaching vehicles), these latter must be either entirely prohibited or restricted to an extent that they no longer constitute a nuisance. Every troublesome illuminated sign or private lighting installation should be absolutely prohibited. As long as these restrictions cannot be enforced, nothing definite can be achieved and it is impossible to install lighting on class I roads which will completely satisfy the specified requirements.

But when all these conditions have been met, it must also be remembered when judging the efficiency and suitability of a lighting system that when a driver experiences a definite stimulus by peripheral vision and he directs his eye on the point from which the stimulus emanates in order to recognise it, a short interval of 0.3 to 0.5 second must elapse before full recognition takes place, even when no movement of the head is necessary and the object is such that binocular vision is still possible; otherwise a much longer interval will elapse. In this interval of time the driver will have

[6]) On approaching, passing and after passing each lamp, simultaneous indirect glare and successive glare are experienced in rapid succession, while on a long straight road the lamps further away produce continuously a simultaneous indirect glare and those lamps in the remote distance even a simultaneous direct glare. Cf. Bouma: The problem of glare in highway lighting, Philips techn. Rev., 1, 225, 1936.

traversed a distance of 22 to 37 feet, assuming he is travelling at 50 m.p.h. Whatever lies within this distance is thus quite unable to produce a conscious reaction. It could still be stipulated that the peripheral stimulus due to an object within this distance of 22 to 37 feet should be so pronounced that a reflex action is immediately initiated to avoid the obstruction. But just this reflex action has led to such serious accidents that, on the other hand, its absence is desirable in these circumstances. This signifies that nothing within the 22 to 37 feet interval can be utilised to judge the efficiency of a lighting scheme or has any bearing on the lighting.

If we assume that under perfectly normal traffic conditions, i.e. no possibility of skidding, or fog, an obstacle appears at a distance of over 33 feet from the vehicle, such that a conscious manipulation by the driver must result, which in the extreme case would mean stopping the vehicle, then the vehicle to conform with the official regulations must pull up within a distance of 64 yards when travelling at a speed of 50 m.p.h. [7]). The authorities regard this distance for pulling up as safe at the speed in question. From the moment the obstacle produces a peripheral sensation to the instant the vehicle is brought to a stop the car would travel 74 yards. Let us examine what in this case could and could not be demanded of the lighting. If the obstacle is located within this distance of 74 yards, the illumination must be required to give an adequate peripheral stimulus and then permit the driver to see the obstacle satisfactorily by foveal vision. But in no case can the lighting be required to prevent a collision within this 74 yard interval, since this distance depends on factors extraneous to the illumination, so that such an accident could also take place in daylight. The opinion often expressed that then the driver should have been driving a little slower is untenable in ordinary circumstances. Means are not provided for safe driving at a speed of 50 m.p.h. and a maximum pull-up distance of 64 yards is not laid down for this speed, in order later to place the blame for an accident on either the driver or the given conditions of visibility, for which neither can be held responsible.

[7]) According to official regulations in the Netherlands, the braking power of vehicles must be such as to pull up the vehicle in a distance expressed in metres equal to the square of the speed expressed in tens of kilometers per hour, thus at 30 km.p.h. the vehicle must be pulled up in 9 m, and at 40 km.p.h. in 16 m, taking as a basis an average retardation of 3.86 m per sec. per sec. The Code de la Route in force in France adopts the same pull-up distance as well as the same retardation, rounded off to 4 m per sec. per sec.

Class II Roads

The type of illumination required on class II roads outside built-up areas depends on the importance attaching to these roads. If the road is considered sufficiently important for the same requirements to be laid down as on class I roads, as well as consideration to be given to pedestrian traffic [8]), then the same remarks as given above for class I roads also apply to class II roads: Lighting provided by permanent equipment, no dependence on the illumination from the vehicles themselves, no disturbing illumination from signalling lamps, traffic indications, illuminated signs or private lighting installations (petrol stations).

If a Class II road is not considered to merit this equivalence with a class I road (the volume of traffic is too small, for instance) and if the road must nevertheless be lighted, it becomes first necessary to require vehicles (and bicyles) to carry lamps; the permanent lighting can then act as a type of beacon lighting. As a result the nature of the lighting scheme is radically altered: In the lighting now needed the lamp itself must be visible, while the actual illumination of the surroundings is a secondary matter. The brightness of the light source may be made low, since it is even then sufficient to render the lamp visible; it also must be low, so low in fact that it never produces a pronounced glare and that the effects due to the evanescent shadows referred to above are entirely avoided. The lighting must follow all bends in the road and indicate their position and direction, but not illuminate them; it is sufficient merely to demarcate them. Where special points require to be made unmistakably conspicuous as road junctions, canal bridges, etc., a more powerful beacon should not be installed at these points as is frequently the case, as it will concentrate the notice of the road user on the lamp itself instead of on the dangerous point. At these points the surroundings must be extra-brightly illuminated, and the lamps used for this purpose should themselves be as inconspicuous as possible. It should be remembered that a beam directed straight ahead from a vehicle approaching from the left or right is now invisible. If this effect is to be retained then suitable reflecting beacons must be set up.

Class III Roads

On class III roads where an unbroken line of

[8]) The question arises whether pedestrians also should be required to carry a signal light in the same way as other road users, since it is pedestrians who are overtaken by vehicles far more frequently than other traffic elements.

beacons will prove too costly, no permanent lighting is provided. Nothing is more dangerous than isolated unscreened lamps at considerable distances apart, which necessarily appear as beacons to the road user likely to deceive him and moreover detract from the utility of his own lamps.

For points which must be specially demarcated the same considerations apply as for class II roads: More powerful illumination of these points, with adequate screening of the lamps.

DEVELOPMENT AND MANUFACTURE OF MODERN TRANSMITTING VALVES

By H. G. BOUMEESTER.

Summary. The improvements which have been made in the various components of transmitting valves, and the developments resulting in modern transmitting valves, are discussed; special reference is made to pentodes, transmitting valves for ultra-short waves and high-power transmitting valves.

Introduction

Since Philips manufactured their first transmitting valves in 1919 considerable advances have been made both in the general construction and applications of these valves. These early transmitting valves were provided with a tungsten filament as a source of electrons and had an anode dissipation measured only in tens of watts. A few years later attemps were made to cool the anodes of these valves with water in order to obtain a greater dissipation. For this purpose the anode was made of a chrome-iron alloy developed in Philips Laboratory and which has the same coefficient of expansion as ordinary glass (100.10^{-7}). In a short time these water-cooled high-output transmitting valves were in widespread use; thus in 1926 thirty valves of type were being employed in parallel at the Postthis Office Radio Station at Rugby. In the space of a decade a whole series of modern transmitting valves was evolved from this laboratory product, such valves now being made by mass production methods and conforming to very strict specifications. The larger valves of this type may be likened to machines which transform direct-current energy into alternating-current energy of practically any required frequency.

These advances were rendered possible, *inter alia*, by the discovery of substances for making the cathodes which were capable of readily emitting electrons. At the same time the grids and anodes were improved, new kinds of glass were evolved for the valves and considerable progress made in perfecting methods of evacuating the valves. Various physical and chemical phenomena which play an important part in the operation of transmitting valves were more closely investigated, such as primary and secondary electron emission, the radiation of energy, and the action of materials capable of absorbing gases (socalled getters), etc. Some general problems relating to the manufacture and the use of transmitting valves are briefly reviewed below.

Electronic Emission from the Cathode

The cathode as the primary source of electrons must satisfy two essential requirements:

1) The requisite rate of electron emission must be obtained with the minimum cathode heating power.
2) The cathode must have a satisfactory life.

Since these two requirements are directly in opposition to one another, a compromise has had to be effected, as is often necessary in technical problems of this kind.

The cathode must satisfy also a number of other requirements. Its behaviour must not depend too closely on the temperature of the surrounding electrodes, and it must also be suitable for use in valves with a comparatively high anode voltage. These conditions can be almost fully met by appropriately forming the electrodes and disposing them suitably within the valve.

Originally, a heated tungsten filament was used as a source of electrons, and even at the present day tungsten is still used in transmitting valves, particularly in valves with water-cooled anodes. The yield of thermal electrons which can be obtained with this form of tungsten cathode is greater the higher the temperature of the filament, but at relatively high temperatures the evaporation rate of the tungsten becomes large and the life of the filament is reduced as a result. An electron output of 5 to 8 mA per watt of cathode heating power can be achieved with a reasonable filament life. There has naturally been a search for materials giving a higher proportionate output of electrons; tungsten filaments with additions of 1.5 to 2 per cent thorium oxide have been made to furnish about 80 mA/W. A still higher yield may be obtained from the oxide-coated cathode consisting of barium-strontium oxide deposited on a metal base of either platinum, nickel, tungsten, copper or a variety of alloys. In the preparation of this cathode a thin layer of barium atoms is produced at the surface, as a result of which the work required for the emission of an electron is so far reduced that a yield of 200 to 300 mA/W is attained.

Still higher values can be obtained by using filament-type cathodes which are comparatively long, thus making the dissipation of heat at the ends of the filament practically negligible.

While oxide cathodes were successfully employed in transmitting valves up to moderately high outputs, their use in high-power and high-tension valves was initially limited by the above-mentioned secondary requirements. Nevertheless, it has been found possible to use oxide cathodes in the largest radiation-cooled transmitting valves, as in the PC 3/1 000 pentode. This valve operates with an anode voltage of 3 000 V, which can however be made higher without adversely affecting the cathode, even up to 4 000 or 5 000 V. But the use of oxide cathodes makes these high voltages quite unnecessary, since an adequate source of electrons is already available and comparatively high anode current and low anode voltages can be employed. This is frequently an advantage when using these valves in small transmitters.

So-called indirectly-heated cathodes are extensively used in receiving valves, but this type of cathode does not offer the same advantages in transmitting valves, although a number of valves, e.g. the PE 1/50 pentode, are fitted with them for other reasons.

Materials for Grids and Anodes

The function of the grid in a transmitting valve is to control the current intensity through the valve. If, in performing this function, the grid itself commences to emit electrons, for instance as a result of heating or of the impact of electrons upon it, the operation of the valve is adversely affected. By suitably cooling the grid, the emission of primary electrons from the grid can always be reduced to such a small value that no interference with the operation of the valve occurs. The dissipation of heat can be promoted by means of cooling ribs, cooling fins, heavy supports, etc., so that the temperature of the grid remains sufficiently low.

In the case of low-frequency amplifying valves, in which the grid has a negative average potential,

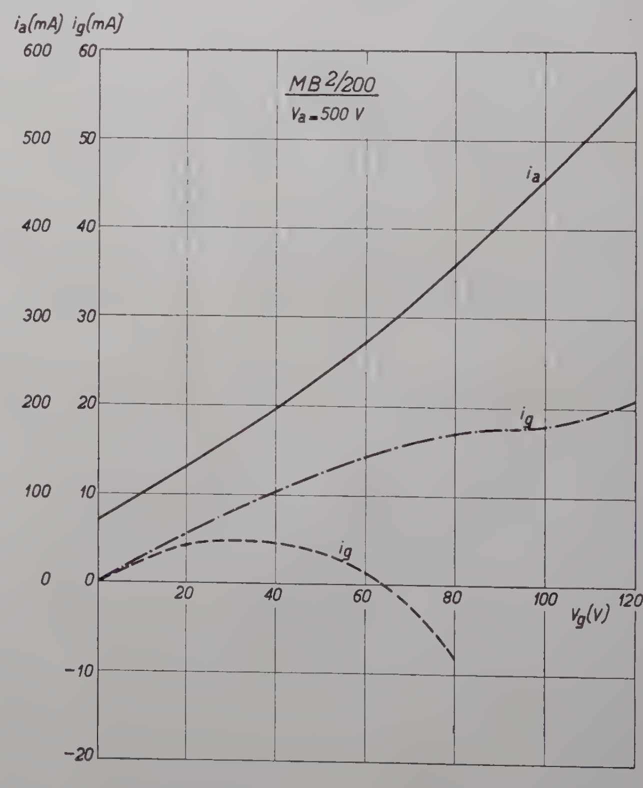


Fig. 1. Grid current i_g and anode current i_a plotted as a function of the grid voltage V_g for the MB 2/200 transmitting valve, for a zirconium —·—·— and for a molybdenum grid ------.

grid current is largely prevented and practically no heat is generated in the grid itself; temperature rise of the grid is almost entirely due to thermal radiation from the anode and cathode. If heat

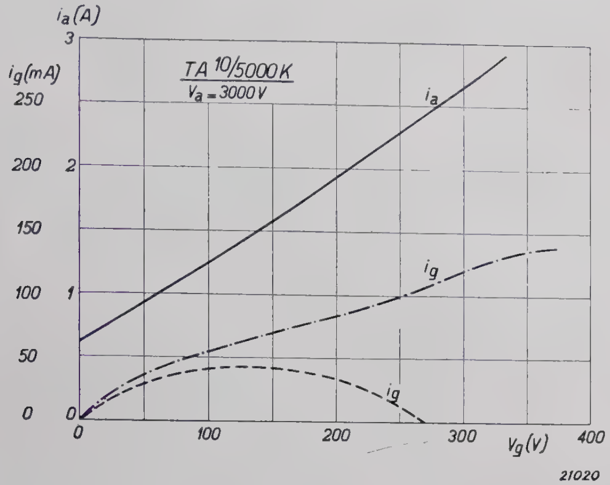


Fig. 2. Grid current i_g and anode current i_a plotted as a function of the grid voltage V_g for the TA 10/5 000 K transmitting valve, for a tungsten grid ------, and for a tungsten grid coated with zirconium oxide — · — · — ·

were evolved at the grid itself, if should be made from a material which would easily radiate heat. On the other hand, in l.f. amplifying valves a substance must be used for the grid which readily reflects heat rays. Silver and copper are suitable for this purpose, and marked success has been obtained with grids wound from coppered wire.

The emission of secondary electrons from the grid can be effectively inhibited by suitably positioning the electrodes with reference to each other and by making the grids of certain materials. The anode current i_a and the grid current i_g in milliamps are plotted as a function of the grid voltage V_g in volts for a 200-watt amplifying valve (MB 2/200) in *fig. 1*. The dash curve was obtained with a molybdenum grid which at high positive grid voltages emits such a large amount of secondary electrons that the grid current does not increase continuously with the grid voltage and even becomes negative at grid voltages exceeding 62 V. On the other hand, the secondary emission is so small with a grid wound from zirconium wire that the grid current i_g rises continuously with the grid voltage, as indicated by the dot-dash curve.

A similar result can also be obtained with a tungsten grid coated with zirconium oxide. In *fig. 2* the anode current i_a in A and the grid current i_g in mA are plotted as a function of the grid voltage V_g in volts for a valve with a water-cooled anode. The dash curve relates to a tungsten grid whose secondary emission at grid voltages above 270 V is so great that the grid current i_g became negative. If the tungsten grid be coated with zirconium oxide, secondary emission is reduced to a reasonably small value, and grid

Fig. 3. The TB 2/250 triode.

current then increases uniformly with the grid voltage, as indicated by the dot-dash curve.

To keep the dimensions of the transmitting valve as small as possible the thermal loading of the anode must be as high as practicable, in other words the working temperature of a radiation-cooled anode must be raised to a level consistent with the need for permanently maintaining a satisfactory vacuum. If the anode is not water-cooled, it is desirable to make the anode of a material which at the specified temperature readily radiates heat. Nickel foil coated with carbon is a good thermal radiator and has been used for many years in valves with oxide-coated cathodes. Graphite anodes have also been used, but these introduce difficulties in valves run at high anode voltages, since occluded gases cannot be readily expelled from the graphite and there is a tendency for small particles to become detached from the anode and cause sparking in the valve.

If the anode is coated with a layer of very finely-divided metal in place of graphite it acquires a black surface also and will then readily radiate heat; hence it is very suitable for use in trans-

mitting valves. Tungsten powder can now be prepared with a mean diameter of 10^{-6} cm per particle.

A triode TB 2/250 is shown in *fig. 3* which has a molybdenum anode coated with a firmly adherent layer of this pulverised tungsten.

Mechanical Construction

Special attention must be devoted to the mechanical construction of valves in view of the need for withstanding transport over long distances and for their use in portable transmitters, and ship and aircraft transmitters. The electrodes are frequently supported by being bonded together and to the glass bulb by means of ceramic insulating distance pieces having suitable electrical characteristics, or with mica supports. To enable a high vacuum to be created and maintained in the valve, these components must be submitted to special treatment before assembly.

The TC 2/300 valve designed for ultra-short waves is shown in *fig. 4* as an example of the mechanical construction of a transmitting valve. The grid and filament are supported by ceramic insulating pieces and insulated from the anode in like manner.

Before leaving the works, transmitting valves are submitted to a shock test which is applied to every large type of valve individually and to random samples in the case of the smaller types. In the arrangement shown in *fig. 5*, 240 shocks per minute are applied to 100 and 250 kW valves for a period of two hours. After this test a radiograph is taken to determine whether the grid and filament have sustained any mechanical damage or have failed to retain their relative positions; finally each valve has to undergo a complete electrical test.

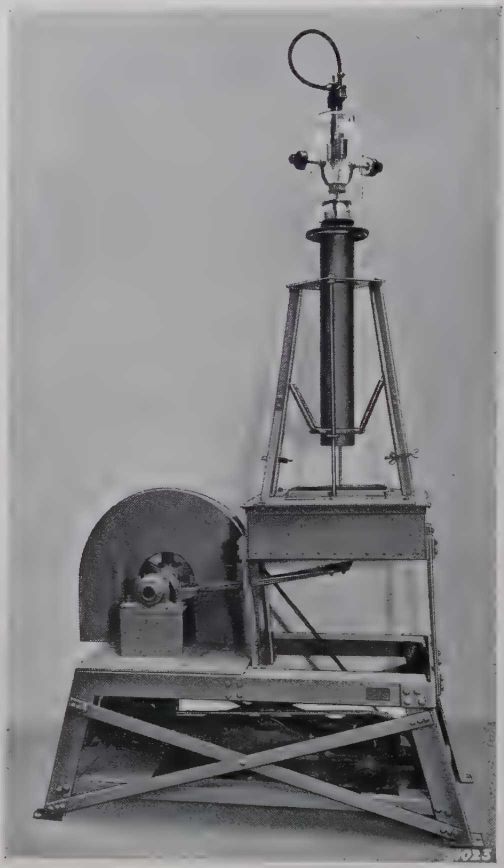


Fig. 5. Arrangement for shock tests on the large TA 20/250 transmitting valve.

Fig. 4. The TC 2/300 transmitting valve. The anode is welded at the top to a chrome-iron plate which is fused to the bulb; at the lower end it is supported against the bulb by a mica disc. The ceramic insulating distance pieces are visible above and below the anode.

Without entering into a detailed description of the various transmitting valves manufactured by Philips, a few examples of the principal types of transmitting valves made by us will be discussed in the light of the above considerations.

Tetrodes and Pentodes

Just as in the course of time, triode receiving valves have given place to screen-grid valves, for the principal reason that a smaller capacity was obtained between the grid and anode, so a similar development has also been followed in the design of transmitting valves. For the last eight years Philips have manufactured a series of tetrodes which dispense with neutrodyning in transmitters.

Another important advance made in recent years in the design of multi-grid valves has been the

appearance of a complete series of pentodes *(fig. 6)*, possessing the advantage of simple and economical modulation at the third grid (suppressor grid). At the same time these valves give a higher efficiency than tetrodes, and are used, for example, in television transmitters. The smallest valve in this series (fig. 1) has an output of 15 watts, the largest radiation-cooled pentode is the PC 3/1000 rated for 1 kW, while the PA 12/15 is water-cooled and has an output of 15 kW.

High-Frequency Transmitting Valves

During recent years there has been a growing demand for transmitting valves operating with a satisfactory efficiency at frequencies exceeding $30 \cdot 10^6$ c/sec, i.e. on waves below 10 m. This class of ultra-short waves is being increasingly used for television purposes, in diathermy and in special signalling systems for military purposes or traffic control.

At these extremely high frequencies, all internal components of the transmitting valves must be made as small as possible, since the times of transit of the electrons cannot be neglected relative to the cycle of the electrical oscillation. In addition the capacities must be small and the leads very short, in order that their inductance remains within reasonable limits. Since the output of the valve must nevertheless be high, they cannot on the other hand be of too small dimensions, so that here again a compromise must be made.

Fig. 7. The TB 1/60 transmitting triode.

A triode TB 1/60 for ultra-short waves is shown in *fig. 7* where it is seen that the leads are extremely short. The anode is made of carbon to obtain a high output (60 W with a wavelength of 4 to 5 m). This valve can also be used for wavelengths down to 1 m., although in these circumstances the output is much reduced.

Another point of considerable importance in ultra-short wave transmitting valves is the high dielectric losses in the insulators, and particularly in the glass forming the bulb. If no precautions are taken to eliminate these losses, a marked heating and the occurrence of electrolytic phenomena in

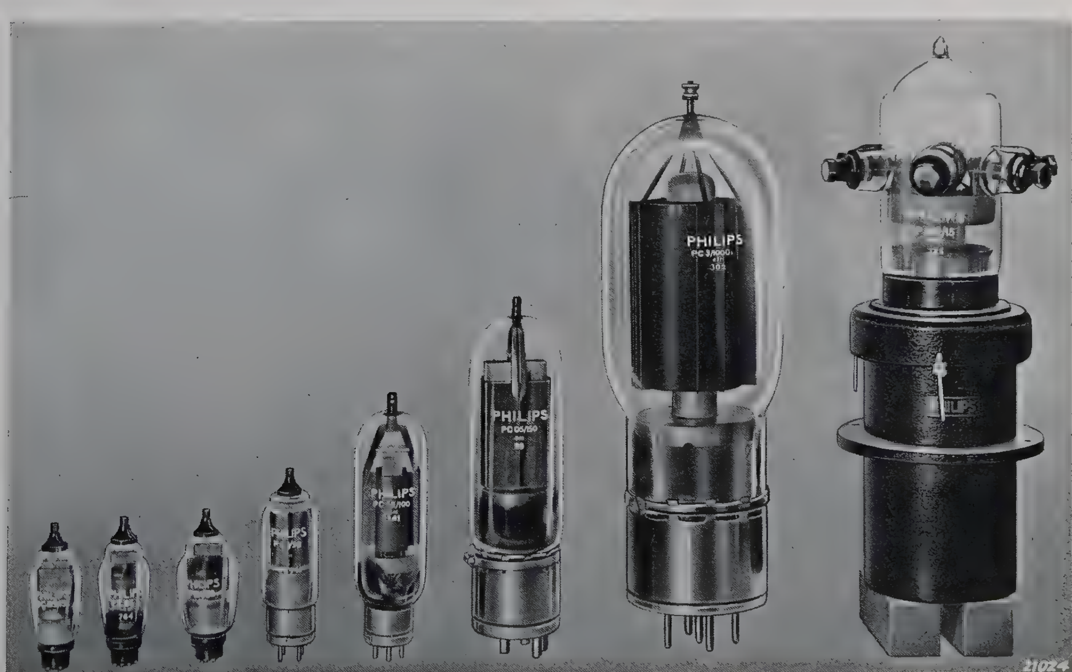


Fig. 6. Series of pentodes of which the smallest has an output of 15 W, the largest radiation-cooled valve PC 3/1 000 with an output of 1 kW and the water-cooled pentode PA 12/15 with an output of 15 kW.

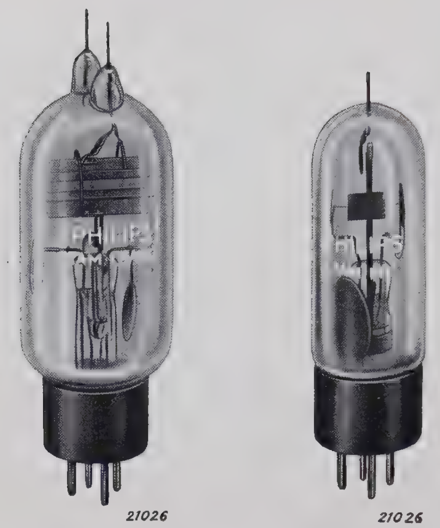


Fig. 8. The TAMM and TAM 1.5/100 magnetron valves.

the glass will result in the destruction of the bulb. In the TC 2/300 transmitting valve shown in fig. 4 the leading-in wires to the various electrodes have therefore been so positioned in the bulb with respect to each other that they are separated by glass walls over a distance which considerably reduces the electrical stress on the glass. This transmitting valve in which the permissible anode dissipation is 300 watts has been designed for use in diathermy apparatus.

For special signalling systems, the frequency band above $300 \cdot 10^6$ c/s is important, i.e. the wave band below 1 m. Single-grid and multi-grid valves are hardly suitable for these purposes since they can never furnish more than a few watts useful output in this frequency band irrespective of the circuit employed. On the other hand, a satisfactory efficiency can be obtained at these low wave-lengths by using valves in which the electrons are deflected during their passage through the axial field of a magnet which may be either an electromagnet or a permanent magnet. These valves are called magnetron valves.

Two magnetron valves of this type are shown in *fig. 8*, viz., the TAMM with two anodes and TAM 1.5/100 with four anodes which are connected crosswise in pairs. At a frequency of $600 \cdot 10^6$ c/s the latter valve has, for instance, an output of 50 to 60 W, with an efficiency of approximately 40 per cent. The first-named valve can still be run effectively at a frequency of $1200 \cdot 10^6$ c/s, having then an output of 7 W and a 10 per cent efficiency. The magnetic field intensity in this case is approximately 1000 oersted. These special transmitting valves are being steadily developed towards higher outputs and higher frequencies.

Water-Cooled Transmitting Valves for Outputs of Over 100 Kilowatts

Philips have manufactured high-power water-cooled transmitting valves for a number of radio transmitters. The largest type, TA 20/250, shown in *fig. 9*, has a useful output of 250 kW on long waves; including the cooler this valve is 1.40 m. high. The filament is made in 12 parts each about $^1/_2$ m long. Owing to the use of a central rod which can slide through two insulators at the top of the valve, a perfectly rigid and self-supporting assembly is obtained. The filament consumes 15 kW (425 A at 35 V). Special measures have to be adopted to lead this powerful current through vacuum-tight seals in the glass, and include water-cooling of the filament supports. The 100-kW valve, the TA 18/100 000 type, operates with a

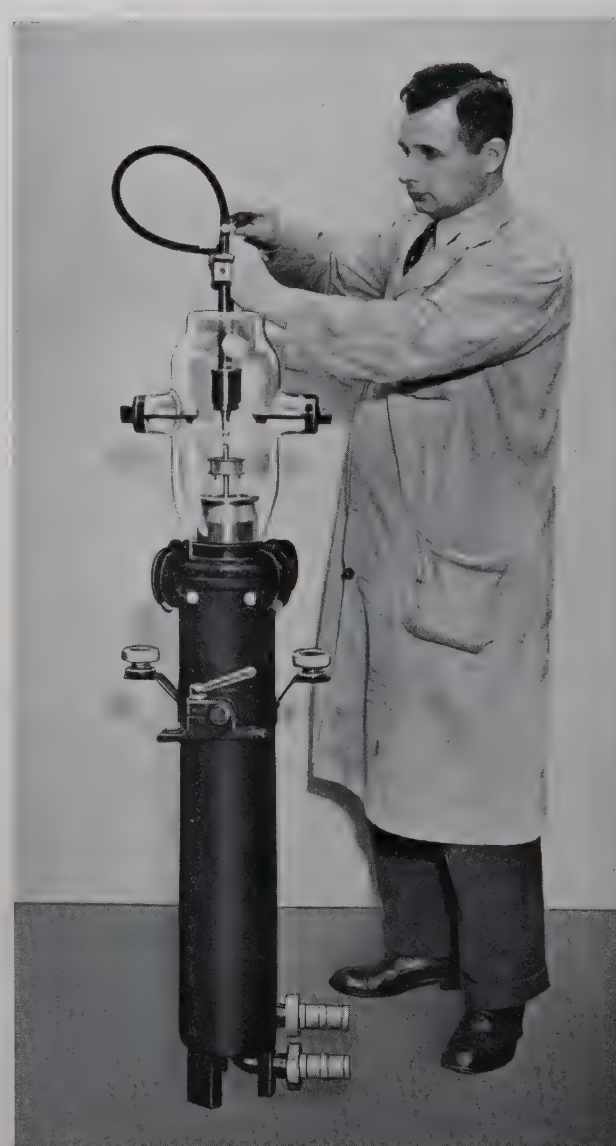


Fig. 9. The largest water-cooled transmitting valve TA 20/250 for an output of 250 kW.

filament current of 207 A. This large current can be passed into the valve without artificial cooling, either by water or air, owing to the provision of a massive chrome-iron cylinder fused to the glass.

To obtain maximum economy in running these valves the anode voltage has been increased to the greatest value consistent with proper functioning of the valve. Thus for the TA 20/250 valve shown in *fig. 9* a maximum anode voltage of 20 000 V is used. To obtain the same output at 10 000 V, the anode current, and hence the filament input, would have to be doubled, and 30 kW filament power would be required in place of the 15 kW actually used. With 5 000 working hours per *annum*, which is normal for a radio transmitter, this would amount to an extra annual consumption of 75 000 kWh per valve.

A special water-circulating system serves for cooling the anode, as shown in *fig. 10*, and ensures that the water flows over the whole of the anode at a uniform rate of 2 m per sec (i.e. a flow of 120 litres per min.). By using this method of cooling, the anode can dissipate 100 W per sq.cm.

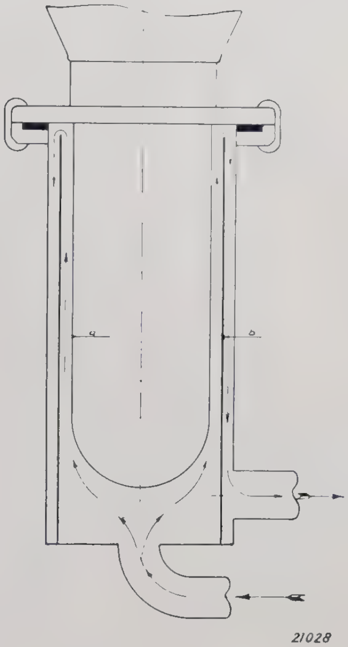


Fig. 10. Flow of cooling water for large transmitting valves. No regions of stagnant water at the anode surface are permissible.

PHYSICAL PRINCIPLES OF GASFILLED HOT-CATHODE RECTIFIERS

by M. J. DRUYVESTEYN and J. G. W. MULDER.

Summary. Some of the principal phenomena occurring in the operation of gas-filled rectifying valves are discussed on the basis of a general analysis of the voltage-current characteristic of a gas discharge. The construction of a number of rectifying valves for different current and voltage ratings is described.

Introduction

While solids and liquids can be classified according to their electrical behaviour into conductors and non-conductors (insulators), gases can behave as either conductors or insulators according to their physical condition. As a rule a gas is an excellent insulator, but if it contains sufficient ions it will become a good electrical conductor. In gas-filled rectifying valves the gas is rendered conducting when the p.d. applied is one particular direction while it acts as an insulator when the p.d. is reversed. This action is obtained in gas-filled rectifying valves by making the electrode acting as cathode during the passage of current in the form of a hot-cathode or by using a mercury cathode. In the present article we shall confine ourselves to hot-cathode rectifiers, and to the physical processes occurring in these valves, omitting for the moment any consideration of the circuits themselves.

Characteristic of a Gas Discharge

To gain an insight into the action of a gas-filled rectifying valve, let us examine in the first place what takes place in a simple gas-discharge tube fitted with two metal plates at a distance of, say,

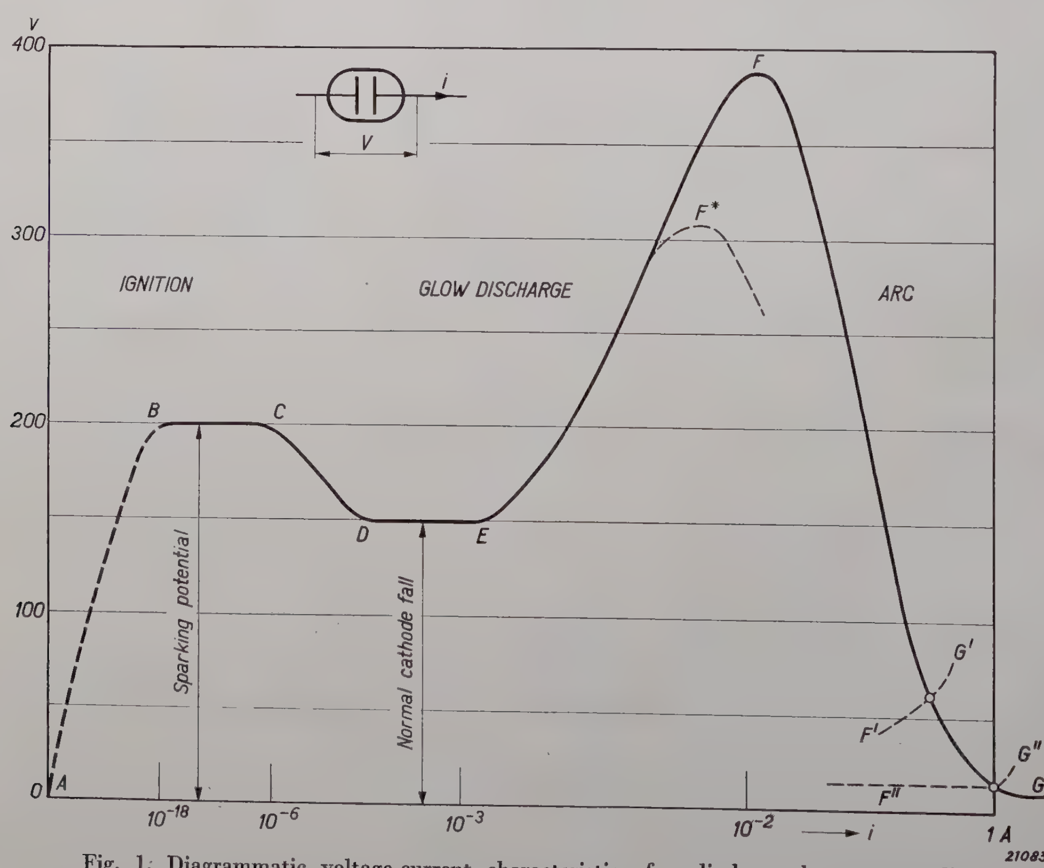


Fig. 1. Diagrammatic voltage-current characteristic of a discharge between parallel plates. Individual current values are indicated on an arbitrary scale to show the order of magnitude of the currents at which different discharge phenomena occur.

1 cm from each other and containing a rare gas atmosphere at a few mm pressure. The characteristic of a valve of this type is shown diagrammatically in *fig. 1*, the curve representing the connection between the impressed voltage and the current flowing through the valve. It is seen from this curve that a gas can act both as a conductor and as an insulator; thus at 20 V a current can flow of approximately 10^{-20} A (along the broken line *AB*) or one of several amperes (at *G*). At a potential difference of 180 V there are in fact four current values. This multiplicity of current values corresponding to a single voltage is a general feature of all gas discharges.

The particular curve illustrated applies not merely to a discharge between parallel plates but is also representative of electrodes having different shapes and disposed in various ways. Nevertheless the characteristic is subject to marked alterations when the electrodes are not contained in the same bulb but are placed, for instance, in two tubes connected by a long tube, as well as when the gas pressure is made abnormally high or low.

Analysing the nature of the different portions making up the characteristic it is found that the very weak current passing in the insulating portion *AB* has its origin in the field attracting towards the electrodes the ions which are present in every gas. At *B* the current increases considerably and so-called ignition takes place. At the striking voltage the field is powerful enough to impart to sufficient electrons a velocity adequate to ionise the gas atoms; the positively-charged ions pass to the cathode (negative plate) and liberate electrons from it. The current increases considerably (*BC*), and as a result space charges are generated which destroy the homogenity of the field; a glow discharge is then obtained (*DEF*). The field is now concentrated in a thin layer of gas at the cathode, where the cathode fall occurs. The potential gradient between the boundary of the cathode fall and the anode (positive plate) is comparatively small. The normal cathode fall [1]) is lower than the striking voltage, this being possible because with the field distribution in question here the electrons abstract more energy from the field for ionisation purposes than during ignition. In the portion *EF* of the curve the cathode fall again increases with increasing current; nevertheless the voltage *V* impressed on the valve and the cathode fall remain roughly equal to one another (this applies from *D* to *G*).

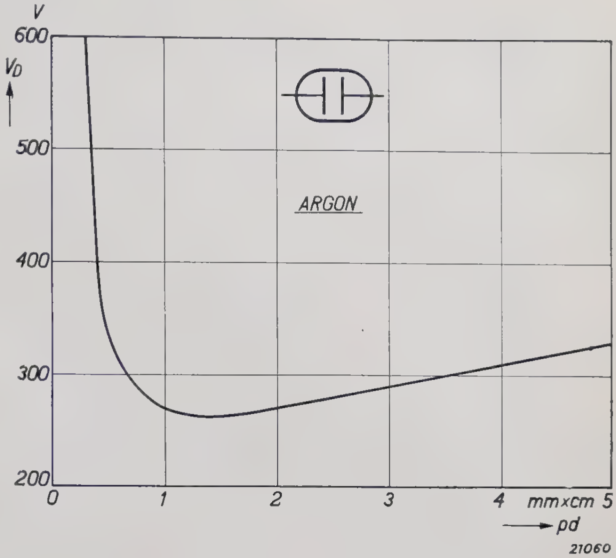


Fig. 2. Ignition voltage V_D for argon across parallel plates as a function of the product of the gas pressure and the distance between the electrodes (Paschen's curve).

Up to this point the electrons are liberated from the cathode by the impact of positive ions, which strike the cathode with a high velocity and heat the cathode more with increasing current. At F a new effect is observed: the temperature of the cathode has been raised so high (with tungsten to approximately 1750 deg. C.) that thermal emission of electrons now begins. Since the electrons are now liberated not merely by positive ions striking against the cathode, the cathode fall can diminish and an arc discharge is obtained at the hot cathode. The arc voltage may become very small, smaller even than the ionisation potential of the gas, and large currents can now flow through the gas. In the portion *FG* (sharp drop in potential with increase in current intensity) the temperature of the cathode rises. The maximum value of the current at a constant cathode temperature is determined principally by the thermal emission of electrons.

If, on the other hand, the current is not altered slowly as assumed above, so as to give time for an equilibrium to be reached, but the variation in *V* is determined for a rapid change in *i*, the cathode temperature being constant, since a certain time is required before this temperature becomes stable, then characteristics will be obtained similar to the dash lines $F'G'$ and $F''G''$, the temperature for $F'G'$ being lower than that for $F''G''$.

The shape of the characteristic in fig. 1 depends on a number of factors, such as the nature of the gas, the material of the cathodes and the gas pressure. The striking voltage is determined by

1) With a normal cathode fall (*DE*) current flows to only part of the cathode while with an abnormal cathode fall (*EF*) the current flows to the whole of the cathode.

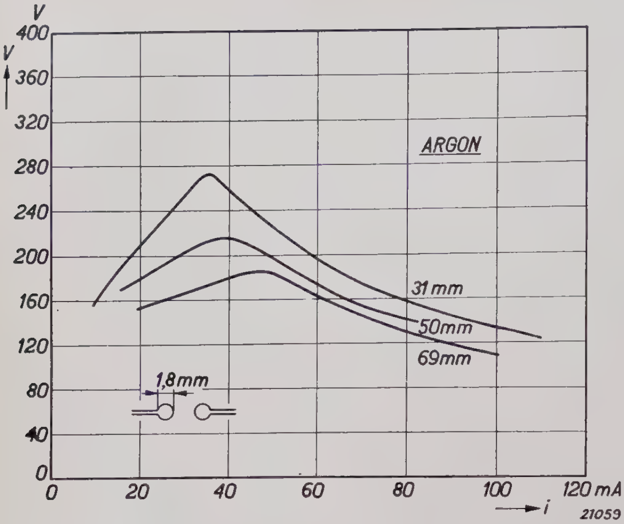


Fig. 3. Transition from a glow-discharge to an arc discharge between tungsten spheres.

the product of the gas pressure p and the distance between the plates d. The relationship for an iron cathode in argon is shown in *fig. 2*.

In *fig. 3* the valve voltage is plotted against the current in the portion *EFG* for different gas pressures, using as electrodes two small tungsten spheres, 1.8 mm in diameter. This shape of electrode was used because of the difficulty of reproducing measurements during the transition from the glow discharge to the arc discharge when using flat electrodes. It is seen from the curves that the slope of the curve portion *EF* is the greater and the maximum voltage higher the lower the gas pressure.

Hot-Cathode Rectifying Valves

In gasfilled rectifying valves, an arc discharge has to be obtained when the p.d. is applied in one direction, while the gas must act as an insulator or at most lead to a glow discharge with the p.d. in the opposite direction. When current flows in the latter direction a discharge is therefore always obtained on one of the two positive-slope sections (*AB* or *EF* in fig. 1). To facilitate the formation of an arc discharge in the direction of current-flow, a hot cathode, usually an oxide-coated cathode, is used in the rectifying valves under discussion here. By means of a heating current, applied either directly or indirectly, this cathode is raised to a temperature at which it can emit electrons. The arc will thus have a characteristic roughly of the type of $F''G''$ in fig. 1.

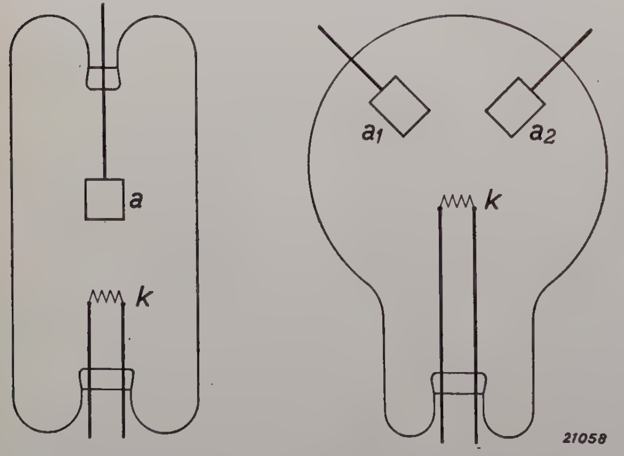


Fig. 4. A single-phase rectifier and a two-phase rectifier both with hot-cathodes.

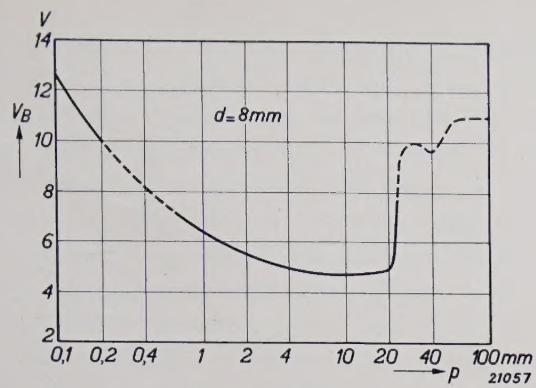
A single-phase rectifying valve with the hot cathode k and the anode a is shown on the left in *fig. 4*. We shall continue to refer to the "anode" a even when it is negative with respect to k and is hence able to act as the cathode for a glow discharge. On the right of fig. 4 is shown a two-phase rectifier with two anodes, a_1 and a_2. In the normal circuits adopted for these valves, at the moment an arc is obtained between k and a_1, a_2 becomes negative with respect to k, and *vice versa*.

The life of a valve is usually limited by the disintegration of the cathode, for during the arc discharge (k — a) the positive gas ions strike the hot cathode with such a velocity that they frequently cause the detachment of atoms. To minimise the disintegration of the oxide cathode the velocity of the ions on impact against the cathode must not be too great. Since at a pressure of less than a few millimetres the positive ions on passing through the cathode fall hardly ever collide with gas atoms and therefore store the total acceleration acquired, the cathode fall must be low to ensure a long life for the valve.

On the basis of fig. 1 we shall discuss the principal phenomena occurring during the arc discharge with a hot cathode (k—, a+) as well as the measures taken to prevent an arc discharge in the opposite direction (i.e. k+, a—); for should such an arc be obtained the valve will no longer function as a rectifier.

Arc Discharge

The variation in potential in the arc discharge of a hot-cathode valve of the type shown in fig. 4 is usually of the following type: Close to the cathode the potential increases sharply over a distance of less than 0.1 mm, so that with an arc discharge there is also a cathode fall (of approximately 15 V). Further away the electrical field intensity is much smaller and the drop in potential is only a few volts; in this region a potential maximum is usually obtained. To reach the anode the electrons must overcome an electrical retarding field, which is possible by



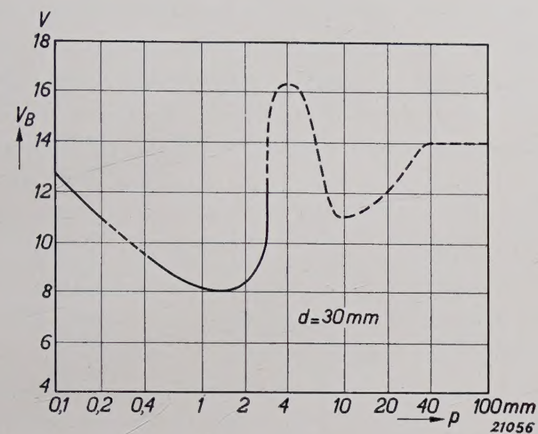


Fig. 5. Arc voltage V_B as a function of the argon pressure at 0.5 A and an electrode gap of a) 8 mm, b) 30 mm.

diffusion. The highly ionised part of the discharge where the field intensity is low is frequently referred to as the plasma. Sometimes the electrical field at the anode again increases in intensity and accelerates the electrons, when an anode fall is produced.

This anode fall, whose value often oscillates, is only obtained when the number of collisions between electrons and gas atoms exceeds a certain critical value. The frequency of these collisions is determined principally by the product of the gas pressure and the distance between the electrodes.

The arc voltage V_B is equal to the sum of the cathode fall, the potential gradient in the plasma and the anode fall. *Fig. 5a* and *b* shows two examples of the arc voltage in rectifying valves with oxide cathodes plotted as a function of the gas pressure (argon). Over the broken portions of the curves low-frequency oscillations in the arc voltage are obtained [2]). It is seen that a minimum value of the arc voltage obtains between pressures of 3 and 20 mm (and between 1 and 2.5 mm). The steep rise (in fig. 5a at 25 mm, and in fig. 5b at 3 mm) is probably due to an anode fall, which occurs at pressures above this value (see *Table I*).

Table I

Distance between cathode and anode	Pressure of argon above which anode fall occurs
8 mm	25 mm
20 mm	8 mm
30 mm	3 mm

The increase in the voltage with diminishing pressure below 1 mm is due to the cathode fall, which increases as the gas pressure is reduced and remains nearly constant at pressures above a few mm. The lowest value of the cathode fall is generally lower than the ionisation potential, which for the rare gases used here lies between 10 and 25 volts.

The increase in the cathode fall with diminishing gas pressure at constant current intensity is the smaller, the greater the dimensions of the cathode used.

We shall endeavour to explain the variation in the cathode fall as a function of the gas pressure. It is assumed here that the cathode fall is determined by the fact that n electrons emitted from the cathode must ionise so many gas atoms that the formed positive ions which arrive at the cathode compensate the space charge of the electrons to such a degree that n electrons are again liberated from the cathode. Up to approximately 100 V the probability of ionisation per collision increases with the velocity of the electrons. It thus follows that at a lower gas pressure, in other words for less collisions, the requisite number of ionisations can only take place at a higher electronic velocity, i.e. with a higher cathode fall. The measured increase in the cathode fall with diminishing pressure is however greater than would follow from the above considerations. A second factor must therefore also operate. The electrons liberated from the cathode are accelerated in the cathode fall, such that a stream of electrons with a high velocity passes into the plasma. This electron stream loses energy both by collision with the electrons and the gas atoms; during the latter ionisation may result, and by the transfer of energy to the slower electrons. While the first means of losing energy is closely dependent on the gas pressure, the second is determined mainly by the concentration of the slower electrons, and will hence depend on the current intensity. Since at low pressures the electrons must traverse a considerable distance before striking

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[2]) While the oscillations of V_B at high pressure shown in figs. 5 and 6 are probably due to the anode fall, this does not apply to the variations occurring at a pressure of 0.3 mm.

a gas atom, it is probable that at high current intensities they will already have parted with their energy to the slower electrons.

It is conceivable that when using a larger cathode the cathode fall will be smaller at a lower pressure, since in this case the current intensity, and hence also the concentration of the electrons in the neighbourhood of the cathode, will be lower, resulting in a reduction in energy transfer from the fast to the slow electrons. Since the cathode fall drops with rising gas pressure the life of the oxide cathode, which is determined by cathodic disintegration, will be increased. Yet if the gas pressure exceeds a few centimeters, the cathode life will again decrease for various reasons.

The interaction between the fast electrons in the electronic stream and the slower electrons in the plasma is clearly shown by a dark layer, the so called dispersion layer[3]), which was recently discovered and which occurs in an arc at a hot cathode. A directional stream of fast electrons issues from the cathode fall; this stream not only imparts energy to the slow electrons but is also dispersed by the latter, such that fast electrons are deflected in all directions and convert a large number of gas atoms into a radiating state. As a result it may occur that close to the cathode less light is radiated than further away. A photograph of this layer obtained at a pressure of 0.05 mm of argon and 2 A current is reproduced in *fig. 6*. The thickness of the layer diminishes with increasing current intensity, since at higher current intensities the concentration of the electrons is greater and dispersion can then more readily occur.

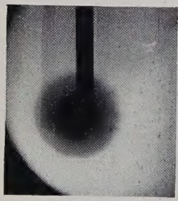

Fig. 6. The dark layer of the cathode fall (0.1 mm thick) and adjoining it the dark "dispersion layer" (2 mm thick) can be seen surrounding the indirectly-heated cathode, which is shown in the photograph as a black spot with bright edge (diameter 4 mm); outside these is the light of the plasma. The edge of the bulb may be seen in the left-hand bottom corner.

Back-Firing

Sudden back-firing may take place in the direction in which the valve should function as an insulator and thus destroy the rectifying action. The glow discharge produced will then become suddenly converted to an arc. Immediately back-firing occurs rectification ceases, so that precautions have to be taken to prevent backfiring or that it occurs at most only very rarely during the normal life of the valve. From fig. 1 it may be concluded that backfiring will not occur as long as the opposing voltage remains below a specified critical value (F, fig. 1).

This conclusion is however not quite valid, since fig. 1 relates to normal conditions of operation and it is specifically stipulated that the cathode is at the same temperature throughout and that this temperature must exceed a certain limiting value to permit an arc discharge to be obtained. Although this corresponds to normal conditions, the temperature distribution on the anode may become non-uniform owing to fortuitous circumstances, when an arc discharge (i.e. back-firing) will occur at the hottest part of the negative anode. Thus already at lower voltages an arc discharge may be obtained (F^* in place of F in fig. 1) than when the temperature distribution is uniform.

In practice back-firing may be produced by a variety of causes[4]). We shall discuss here only such backfiring as is caused by the partial heating

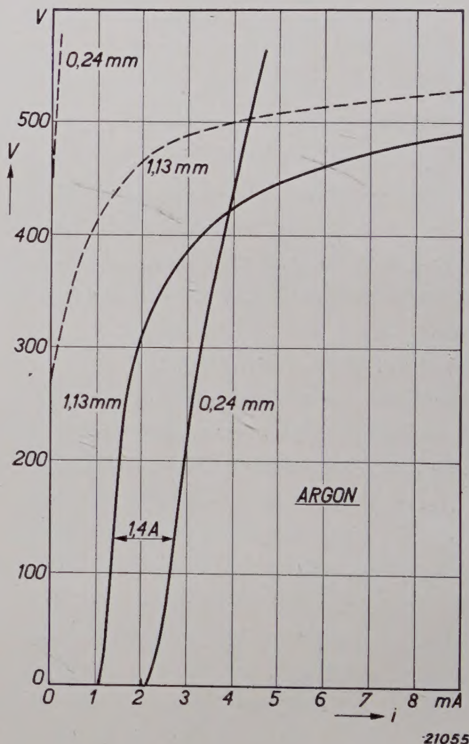

Fig. 7. Connection between current i and voltage V of an anode of a two-phase rectifier, at pressures of 0.24 and 1.13 mm, the current flowing to the other anode being either 1.4 A (continuous line) or nil (dash line).

of the anode just referred to. The danger of back-firing may be minimised by making the anode of a material with a low thermal emission, such as graphite: Although the heating effect produced is greater in the direction of current flow, the current

[3]) M. J. Druyvesteyn and N. Warmoltz, Physica, **4**, 51, 1937.
N. Warmoltz, Nature **138**, 26, 1936.

[4]) Another cause for back-firing should also be mentioned: As soon as a particle, preferably conducting, strikes against the cathode of a glow discharge, there is the possibility that the glow discharge will be transformed to an arc, the point of impact of the metal particle on the cathode acting as the cathode spot.

and voltage in the cut-off direction have also an important bearing on back-firing, since at a given anode temperature the liability of back-firing increases very rapidly as the current and voltage are raised. At lower pressures the danger of back firing is less, for according to fig. 3 the glow discharge current falls, while the maximum voltage increases as the pressure drops. In polyphase rectifying valves the current flowing to a negative anode is greater than the glow-discharge current, because the positive ions of the arc discharge between the cathode and one of the other anodes diffuse to the negative anode. *Fig. 7* shows these conditions for a two-phase valve of the type shown in fig. 4. The current of the negative anode is here plotted as a function of the p.d. at this anode, a current of 1.4 A flowing to the other anode.

Construction of Rectifying Valves [5])

In service, rectifying valves have to meet a variety of requirements, such as a long life and high efficiency (in other words a low arc voltage), as well as freedom from back-firing at the normal currents and voltages used. The various points discussed above have resulted in a variety of designs each conforming to specific practical requirements.

Rectifiers for different current ratings and the same voltage differ mainly in the dimensions of the hot cathode and of the anode and in the capacity of the bulb, particularly the latter since its surface area determines the temperature. The surface of the bulb must be the greater the greater the amount of energy liberated in the valve, i.e. the higher the current intensity.

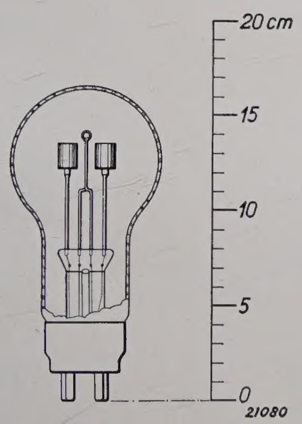

Fig. 8. Two-phase rectifier (type 367 for 6 A and 24 V).

Rectifiers for different voltage ratings and the same current differ mainly in the nature of the gas filling (gas mixture and pressure), as well as in the means adopted for the mutual screening of the electrodes against the action of discharges at undesirable points or at undesirable moments. In view of this the discharge gap is usually made much longer for high voltages, although at exceptionally low pressures (when as in the case shown in fig. 2 the valve is operated to the left of the minimum) the gap must be made very short.

One of the simplest types of two-phase valves, rated for 6 A direct current and 24 V direct voltage, is shown in *fig. 8*. The cathode is a tungsten coil wound with a second wire of thinner gauge which serves to carry the barium oxide. The wedge-shaped slots provide good adherence for the oxide. In rectifiers for higher currents the second wire is also coiled in order to increase the effective surface (e.g. the "Triarlita" cathode shown in *fig. 9*).

The two anodes consist of graphite blocks across which a maximum potential difference of 85 V is obtained, the gas filling being of argon. At the gas pressure chosen, there is no likelihood of a glow discharge between the anodes at this particular

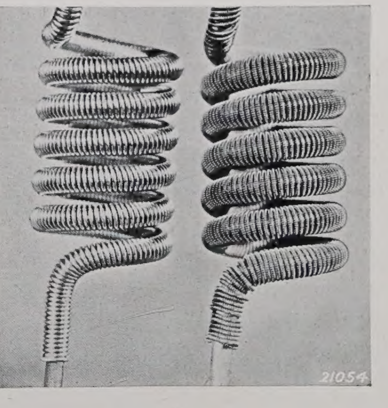

Fig. 9. Single coiled cathode (left) and "Triarlita" coiled-coil cathode (right). The windings have been removed at the bottom to show the cores.

voltage rating. The discharge gap is short and wide so that the above-mentioned theoretical considerations regarding the arc discharge are applicable here. Rectifiers of this type are made for various current ratings up to 60 amps.

For higher voltage ratings certain modifications must be made in the general design of the rectifiers described above. The gas pressure is usually reduced, and for very high voltages is made very low, down to about 10^{-3} mm of mercury, while the leads, especially those to the anode, have to be insulated to prevent undesirable discharges (see *fig. 10*).

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[5]) For detailed data, cf. J. G. W. Mulder, Diss. Delft, 1934.

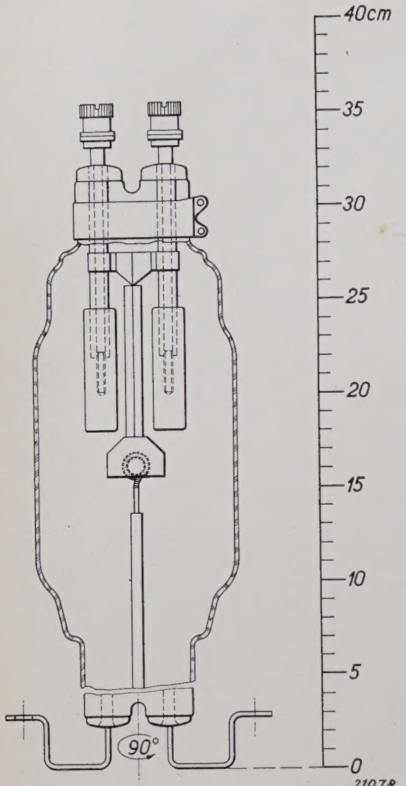

Fig. 10. Two-phase rectifier (type 1069 k for 60 A and 60 V).

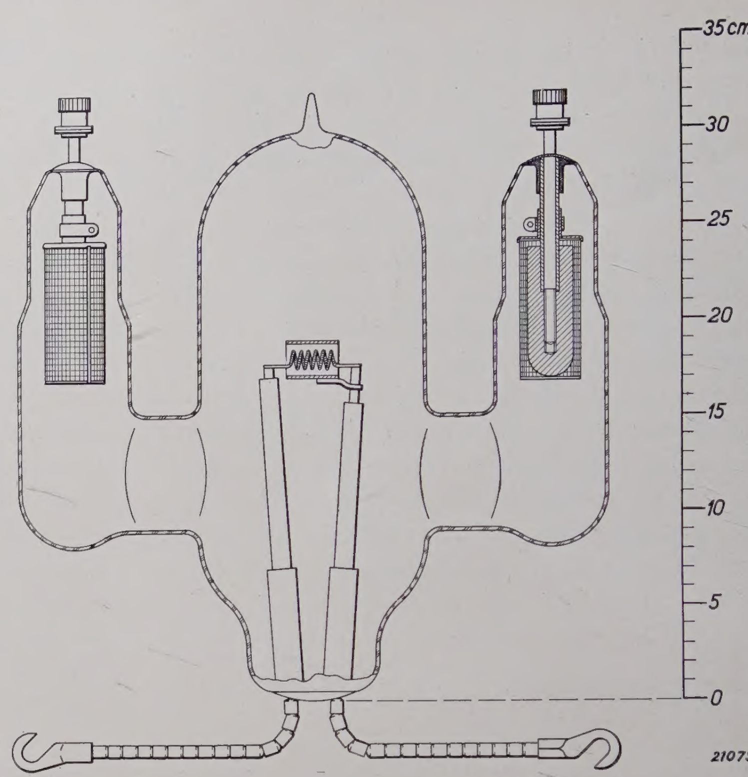

Fig. 11. Two-phase rectifier (type 1554 for 40 A and 250 V).

In all rectifiers for voltages above 40 volts the cathode is located in a space which is partly separated from the remainder of the discharge bulb. This may be done, for instance, by fixing a short tube or a small metal cap round the cathode (fig. 10). In this type of rectifier for current ratings of 60 amps and voltages up to 60 volts (Philips welding rectifier) the cap is open at the bottom, while for higher voltages the cathode is totally enclosed by a coaxial cylinder (up to ratings of about 110 volts). In both cases the effect produced is twofold: In the first place, particles which become detached from the cathode surface are prevented from reaching one of the anodes, these being liable to initiate back-firing, and secondly the current flow diverted from one anode to another by diffusion from the arc discharge is reduced (see fig. 7).

At still higher voltages the design is taken a step further and both anodes and cathodes are accommodated in separate chambers. *Figs. 11* and *12* illustrate examples of these rectifiers. The cathode in these rectifiers is located in the central chamber, and the anodes in fig. 11 are accomodated in two side tubes connected to the central chamber by narrow arms [6]).

In the rectifier shown in fig. 12 the cathode is situated in the top bulb which is connected to the main bulb by a short metal tube. This rectifier has already been illustrated and described in this Review (volume I, p. 163). The greater the divergence in the design of the bulbs from the simple type shown in fig. 4, the more will the discharge phenomena occurring differ from the conditions analysed for this simple type.

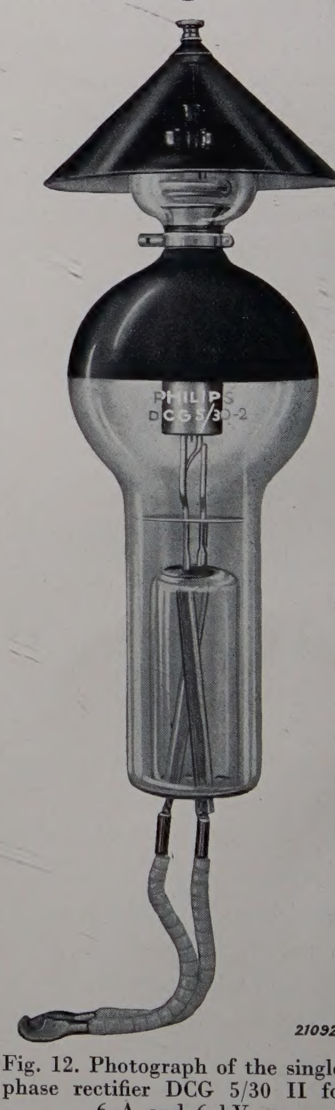

Fig. 12. Photograph of the single-phase rectifier DCG 5/30 II for 6 A and 6 kV.

[6]) In the rectifier shown in fig. 11 a part of the anode surface is screened against a glow discharge in the negative phase. Since this discharge (in the portion *EF*, fig. 1), contrary to the arc discharge in the direction of current flow, tends to spread over the whole surface, the glow-discharge current can be reduced by means of an adequately-insulated grid which partially surrounds the anode at a short distance; this arrangement does not affect the arc discharge and barely reduces the radiation of heat from the anode through the grid.